Transforming Systems Engineering through Model-Centric Engineering

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Acknowledgments

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We want to thank the team of developers from NASA/JPL, the OpenMBEE Collaboration group, and our RT-168 Research collaborators that contributed to the configured and deployed OpenMBEE integration modeling environment that is hosted on Amazon Web Services server that provides our Authoritative Source of Truth for the Surrogate Pilot Experiments. We also want to thank the commercial organizations that have provided modeling and analysis tools that are used in the pilot, which have been provided under academic licensing agreements.

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Executive Summary

This is the final technical report of the Systems Engineering Research Center (SERC) research task RT-195. This research task (RT) addresses research needs extending prior efforts under RT-48/118/141/157/170 that informed us that Model-Centric Engineering (MCE) is in use and adoption seems to be accelerating. The expected capability of MCE and more broadly Digital Engineering (DE) can enable mission and system-based analysis and engineering that reduces the typical time by at least 25 percent from what is achieved today for large-scale air vehicle systems. The overarching time line from the start of the research until today is:

- 2013-2015: Global scan of most holistic approaches to MCE/DE
- 2015: NAVAIR leadership decides
  - Move quickly to keep pace with other organizations that have adopted MCE
  - Transform, not simply evolve, in order to perform effective oversight of primes that are using modern modeling methods for mission and system engineer
- 2016: NAVAIR leadership decides to accelerate the Systems Engineering Transformation (SET) based on a new SET Framework concept
- 2017: Systematic planning of six (6) Functional Areas, including SERC Research
- 2017 - late: Surrogate Pilot Experiments kickoff to characterize, assess and refine SET Framework approach to Model-based Acquisition, for a new operational paradigm between government and industry
- 2018: Phase 1 of Surrogate Pilot experiments complete with mission, systems and a model for the Request for Proposal (RFP) Response from Surrogate Contractor for Surrogate Pilot experiments
  - Demonstrates art-of-the-possible doing “everything” in models using new operational paradigm between government and industry in a Collaborative Authoritative Source of Truth (AST)
  - Surrogate contractor RFP response refines mission and system models, and provides detailed design and analysis information using multi-physics and discipline-specific models
  - Conducted Digital Signoff for source section technical evaluation directly in the RFP response model
  - Phase 1 results and models provide evidence/examples of unclassified models to support workforce development and training
- 2019: Start of Phase 2
  - Aligning surrogate pilot experiments with SET priorities
  - Outreach to industry to extend participation in Phase 2 experiments for other mission and system scenarios using an AST for government and industry collaboration

The SET team developed the plan for rolling-out SET to NAVAIR, which defined six major Functional Areas as represented in Figure 1 that includes:

- SET Research (conducted by the SERC, and discussed in this report)
- Workforce & Culture
- Integrated Modeling Environment
- Process & Methods
- Policy, Contracts and Legal
- SET Enterprise Deployment (and Surrogate Pilot Experiments)

A key decision by NAVAIR leadership in 2017 was to conduct a surrogate pilot as reflected in Figure 2. The surrogate pilot is using experiments to simulate the execution of the new SET Framework, shown in Figure 3. These Functional Areas have other sub functions as part of the overall effort, and the Surrogate Experiments are being conducted using multi-phase surrogate pilot use cases as part of the SET Enterprise Deployment. The SET Research is being performed in the context of the surrogate experiments. The broader impacts of this research to the other sub functions of SET is also reflected by the dash boxes. This research provides analyses into NAVAIR enterprise capability and builds on efforts for cross-domain model integration, model integrity, ontologies, semantic web technologies, multi-physics modeling, and model visualization that extend RT-157 and RT-170 research to address the evolving SET needs and priorities of SET.

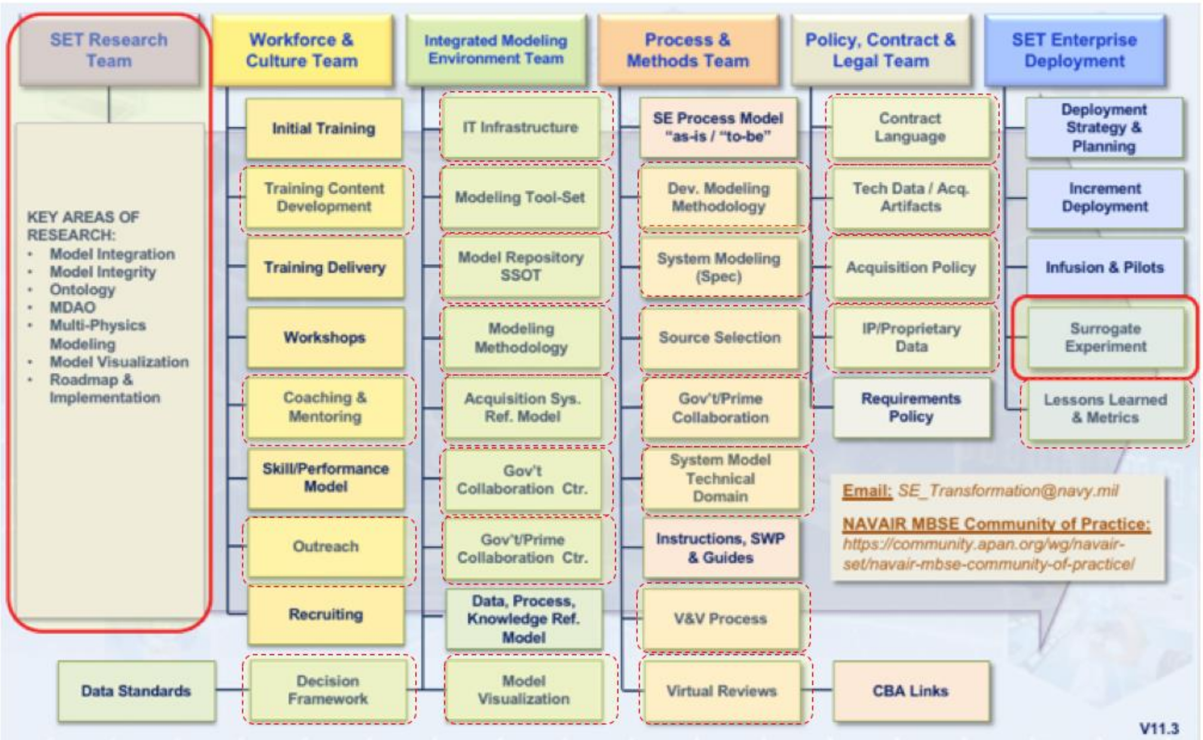

Figure 1. SET Functional Areas with Impacts on SET Research and Surrogate Pilot[1]

[1] This is not the most up-to-date SET Functional Area image, but this image has a NAVAIR Public Release 2018-194. Distribution Statement A – "Approved for public release; distribution is unlimited."

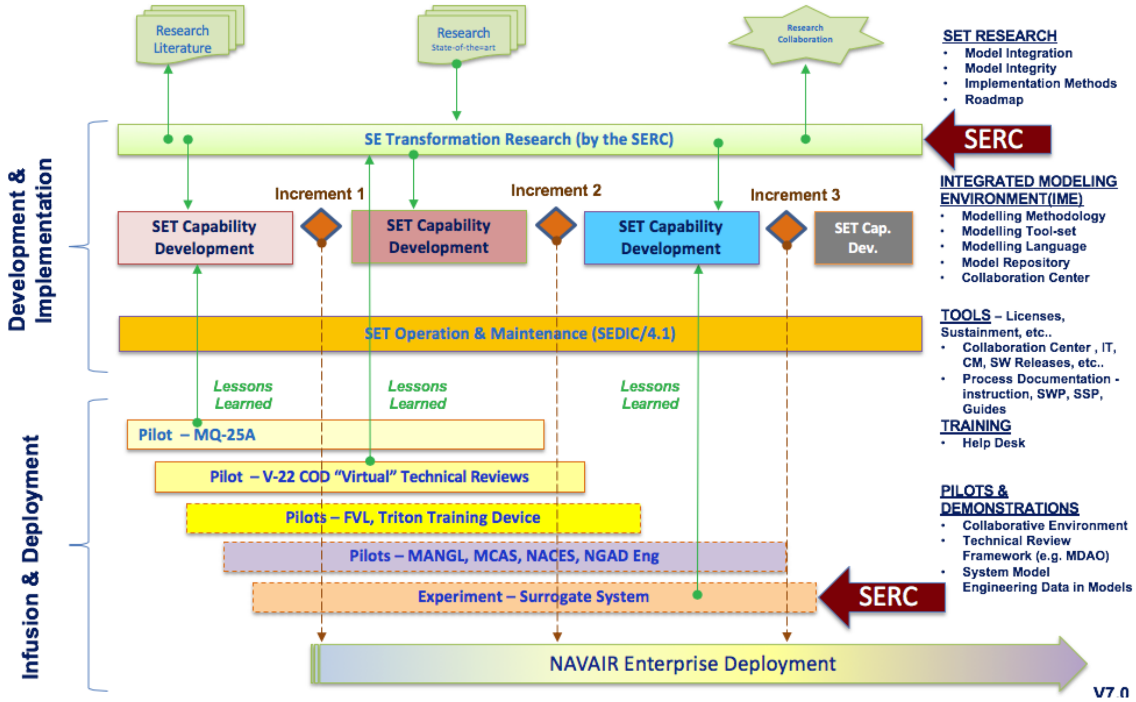

Figure 2. SE Transformation "Roll out" Strategy[2]

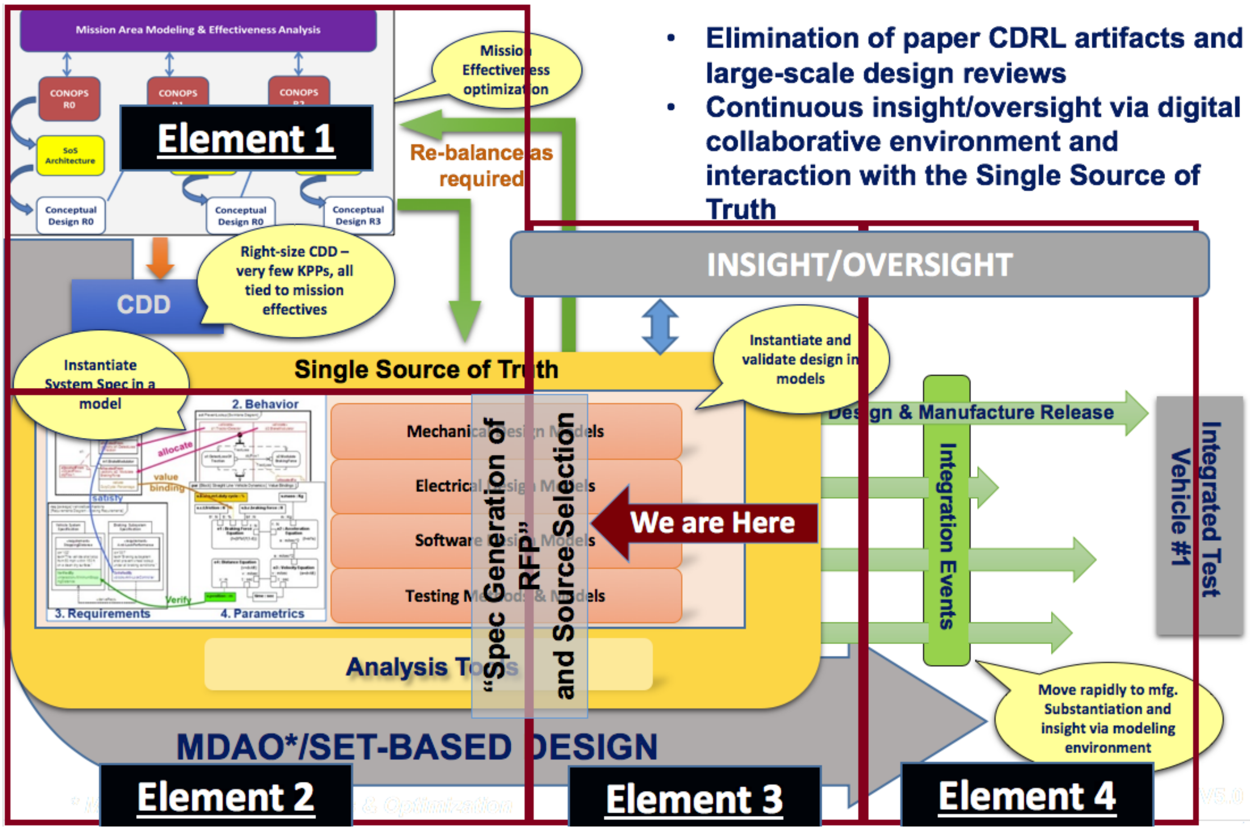

Figure 3. NAVAIR Systems Engineering Transformation Framework[3]

[2] NAVAIR Public Release 2017-892. DISTRIBUTION STATEMENT A – "Approved for public release; distribution is unlimited"

[3] NAVAIR Public Release 2017-370. Distribution Statement A – "Approved for public release; distribution is unlimited"

The Surrogate Pilot Experiments discussed in this report provide demonstrations of the art-of-the-possible for many of the cross-cutting objectives of DE; this includes integrating different model types with simulations, surrogates, systems and components at different levels of abstraction and fidelity and provide an enduring AST across disciplines throughout the lifecycle. The integrated perspectives provide cross-domain views for rapid system level analysis allowing engineers from various disciplines using dynamic models and surrogates to support continuous and often virtual verification and validation for trade space decisions in the face of changing mission needs.

The surrogate experiments attempted to “model everything” in order to show that the concept was possible. The team has demonstrated the feasibility of using modeling methods at the mission, systems, and even using models for the request for proposal (RFP), statement of work, and source selection technical evaluation. The surrogate contractor RFP response models link to the government mission and system models. The surrogate contractor RFP response models includes multi-physics analyses and early design models that illustrate the potential to have deep insight into the design of a proposed air vehicle system prior to contract award. The use of digital signoff directly in the model provides evidence of a new approach for transforming traditional Contract Data Requirement Lists (CDRLs), by documenting and linking digital signoffs with the evidence directly in the models.

The pilot is developing an experimental UAV system called Skyzer, and Phase 1 performed a deep dive on search and rescue mission operational scenarios. This report discusses progress and lessons learned during the Phase 1 and efforts planned for Phase 2 of this surrogate pilot experiments, where the surrogate team developed:

- Surrogate Project/Planning Model
  - Characterizes the objectives for the surrogate pilot and research
  - Discussed in more detail in this report
- Project Planning Model for Skyzer
- Surrogate Mission Model for Skyzer
  - Parts of mission model provided as Government Furnished Information (GFI)
- Surrogate System Model for Skyzer
  - Parts of system model provided as GFI
- Surrogate Acquisition Model Skyzer, includes models for:
  - Statement of Work
  - Technical Evaluation Criteria formalized as a model to support source selection
- Surrogate Contractor System RFP model for Skyzer
  - Surrogate contractor assessed, refined and extended GFI system model
  - Traces back to Government Skyzer System and Mission models
- Surrogate Contractor Design models for Skyzer
  - Design models address aspects of multi-physics analysis and design
  - Links disciplines-specific design back to Surrogate Contractor system, which traces back to Government Skyzer System and Mission models
- View and Viewpoints for DocGen and other Libraries
  - Used to generate the specifications from the models based on stakeholder views
- Collaboration Environment for the Authoritative Source of Truth

The focus has been on learning about a new operational paradigm between government and industry in the execution the SET Framework, not necessarily on an air vehicle design. Many of the detailed facets from the surrogate pilot experiments are discussed in this report and are shared on the All Partners Network (APAN) to socialize these new operational concepts, and to solicit feedback from industry, government and academia.

In April 2018, the three Navy system commands (SYSCOM) NAVAIR, NAVSEA and SPAWAR initiated a plan to build Navy and DoD interoperable ontologies. This effort is also jointly led by our RT-195 team and NAVAIR sponsors. The initial effort focused on using ontology architecture to scope the identified need, enforce interoperability, creating common terminology across domains, and be an enabler for MCE/DE. The progress on the surrogate pilot has been briefed at cross SYSCOM technical interchange meetings and other events, as well as to other government organizations. This research supports additional facets of the SET Transformation and are discussed further in this report.

Our SERC team helped coordinate bringing in industry as part of a peer review in August of 2018 to openly discuss almost any facets of an Acquisition System Reference Model. This provides industry with the opportunity to make constructive comments on representation and content that will likely be provided as “System Model(s)” as GFI as part of future solicitations such as Request for Information (RFI) or Request for Proposals (RFPs).

The strategic plans of SET and overarching goals of this research have been expanded beyond RT-170. RT-195 has support from research collaborators from Georgia Tech, Massachusetts Institute of Technologies and University of Maryland. This report blends RT-170-related accomplishments into this report to document the ongoing progress in support of the NAVAIR SET. We are also working collaboratively with US Army Research, Development and Engineering Command (RDECOM) Armament Research, Development and Engineering Center (ARDEC) in Picatinny, NJ under RT-168 and the follow-on SERC research task ART-002, and some of the results are from synergies derived from that research. We are also leveraging research efforts from RT-176 Naval Postgraduate School Collaborators.

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PART I: RESEARCH TASK OVERVIEW

Part I of this report provides and overview of this research task, including the surrogate pilot experiments and sets the context for the needed research as defined and evolved by our sponsor, as well as the objectives, scope and organization of this report. This part also provides a summary of the current set of research use cases, our Phase 1 & 2 efforts, status, events, demonstrations, deliverables, models, prototype tools and recommendations based on our increased understanding of the research objectives.

1 INTRODUCTION

In 2013, the Naval Air Systems Command (NAVAIR) at the Naval Air Station, Patuxent River, Maryland initiated research into a Vision held by NAVAIR's leadership to assess the technical feasibility of a radical transformation through a more holistic model-centric system engineering (MCSE) approach. The expected capability of such an approach would enable mission-based analysis and engineering that reduces the typical time by at least 25 percent from what was achieved at that time for large-scale air vehicle systems using a traditional document-centric approach. The research need included the evaluation of emerging system design through computer (i.e., digital) models.

Through Systems Engineering Research Center (SERC) research tasks (RT-48, 118, 141, 157, 170) starting in August 2013 there was considerable emphasis on understanding the state-of-the-art through discussions with industry, government and academia [25] [32] [39]. The team, comprised of both NAVAIR and SERC researchers, conducted over 30 discussions, including 21 on site, as well as several follow-up discussions on some of the identified challenge areas and approaches for a new operational paradigm between government and industry.

In 2015, the NAVAIR leadership concluded that they must move quickly to keep pace with the other organizations that have adopted MCE as the pace of evolution is accelerating enabled by rapidly evolving technologies. NAVAIR made the decision to press forward with a Systems Engineering Transformation (SET). In March of 2016, there was a Change of Command at AIR 4.0 (Research and Engineering) and NAVAIR leadership decided to accelerate the SET. Our research sponsor, Mr. David Cohen proposed a new operational paradigm referred to as the SE Transformation Framework that has evolved into the concept depicted by Figure 3. The research efforts starting in 2017 under RT-170 started developing a surrogate pilot concept to assess and refine the execution of the SET Framework through a series of experiments conducted as evolving pilot projects. The emphasis was on a new operational paradigm to mission and systems engineering, analysis and model-based acquisition, which would be led by NAVAIR with collaborative design efforts led by industry. We participated with our sponsors in more industry meetings to assist in communicating and clarifying these concepts for a new type of collaboration, and to assess the impacts on the NAVAIR enterprise, from both a technical and socio-technical perspective. Many objectives for assessment and refinement of the SET Framework are characterized as objectives and captured as part of a Surrogate Pilot Project plan and model that is being traced to experiment models, demonstrations, results and lessons learned.

Briefly, as articulated by our sponsor, the concept of the new SET Framework for transforming from a document-centric process with monolithic reviews to an event-driven model-centric approach involves, but is not limited to:

- A concept for collaborative involvement between Government and Industry to assess mission and System of Systems (SoS) capability analyses, where NAVAIR has the lead to:
    - Involve industry in SoS capabilities assessments during mission-level analysis (to the degree possible)
    - Iteratively perform trade space analyses of the mission capabilities using approaches such as Multidisciplinary Design, Analysis and Optimization (MDAO) as means to develop and verify a model-based specification
    - Synthesize an engineering concept system model characterized as a model-centric specification and associated contractual mechanism based on models or associated formalism
- At the contractual boundaries, industry will lead a process to satisfy the conceptual model addressing the Key Performance Parameters (KPPs), with particular focus on Performance, Availability, Affordability, and Airworthiness to create an Initial Balanced Design
    - Industry too applies MDAO at the system and subsystem level
    - There is a potential need to iterate back to re-balance the needs if the trade space analyses of the solution/system for the program of record (POR) cannot achieve mission-level objectives
    - All requirements are tradeable if they don't add value to the mission-level KPPs
    - These are asynchronous activities in creating an Initial Balanced Design
    - Government and Industry must work together to assess "digital evidence" and "production feasibility"

Another objective for this new operational paradigm is to replace large-scale document-centric reviews such as Systems Requirements Review (SRR), System Functional Review (SFR), Preliminary Design Review (PDR), etc. with continual event-driven reviews using objective or subjective evaluation based on model-centric information. Some initial surrogate pilot demonstrations illustrated a potential approach to replace large-scale document-centric reviews with continual event-driven reviews directly within the model using objective and subjective evaluation based on model-centric information and digital signoffs, where the digital signoff is linked to the model evidence satisfying some criteria typically required at a formal review or as defined in a CDRL. A collaborative AST is being used in the surrogate pilot and is playing a key role with the continuous asynchronous reviews. NAVAIR needs some type of decision framework to assess evolving design maturity with considerations of value to the KPPs, risk and uncertainty. This surrogate pilot experiments factor in these and other types of objectives.

Early in 2017, the SET team developed the plan for rolling-out SET to NAVAIR, which defined six major Functional Areas as represented in Figure 1 that includes:

- SET Research (conducted by the SERC, and discussed in this report)
- Workforce & Culture
- Integrated Modeling Environment
- Process & Methods
- Policy, Contracts and Legal

- SET Enterprise Deployment (and Surrogate Pilot Experiments, also discussed in this report)

These Functional Areas have other sub functions as part of the overall effort, as shown in Figure 1. The Surrogate Experiments are being conducted using multi-phase Surrogate Pilot use cases are part of the SET Enterprise Deployment. The SET Research is being performed in the context of the surrogate experiments. The broader impacts of this research to the other sub functions of SET is also reflected by the dash boxes.

The SET Surrogate Experiments are elaborating mission and system analyses and requirements using a hypothetical system called Skyzer. Skyzer has a Concept of Operations (CONOPs) for an UAV that provides humanitarian maritime support use cases (e.g., search and rescue) as reflected in Figure 4. Phase 1 of the Surrogate Pilot officially kicked-off on December 7, 2017. The timeline of events for the Surrogate Pilot planning and execution are shown in Figure 5. Phase 1 had a very narrow scope in order to focus on the execution through the SET Framework Elements (1-4) as quickly as possible. The scope of the UAV design as requested by our sponsor included multi-physics design considerations that are based on Computational Fluid Dynamics (CFD), topology optimization, structural analysis, weight and vehicle packaging. The surrogate pilot team officially released the RFP concluding the Phase 1 Element 1 & 2 efforts. Performance constraints such as speed of 170 knots forced the design to be something other than a traditional helicopter and ultimately a design similar to the Bell Eagle Eye was proposed in the surrogate contractor RFP response models, which was evaluated in a surrogate source selection by the government team. The efforts moving forward are to align efforts with the SET priorities for the Phase 2 use cases, as reflected in Figure 6.

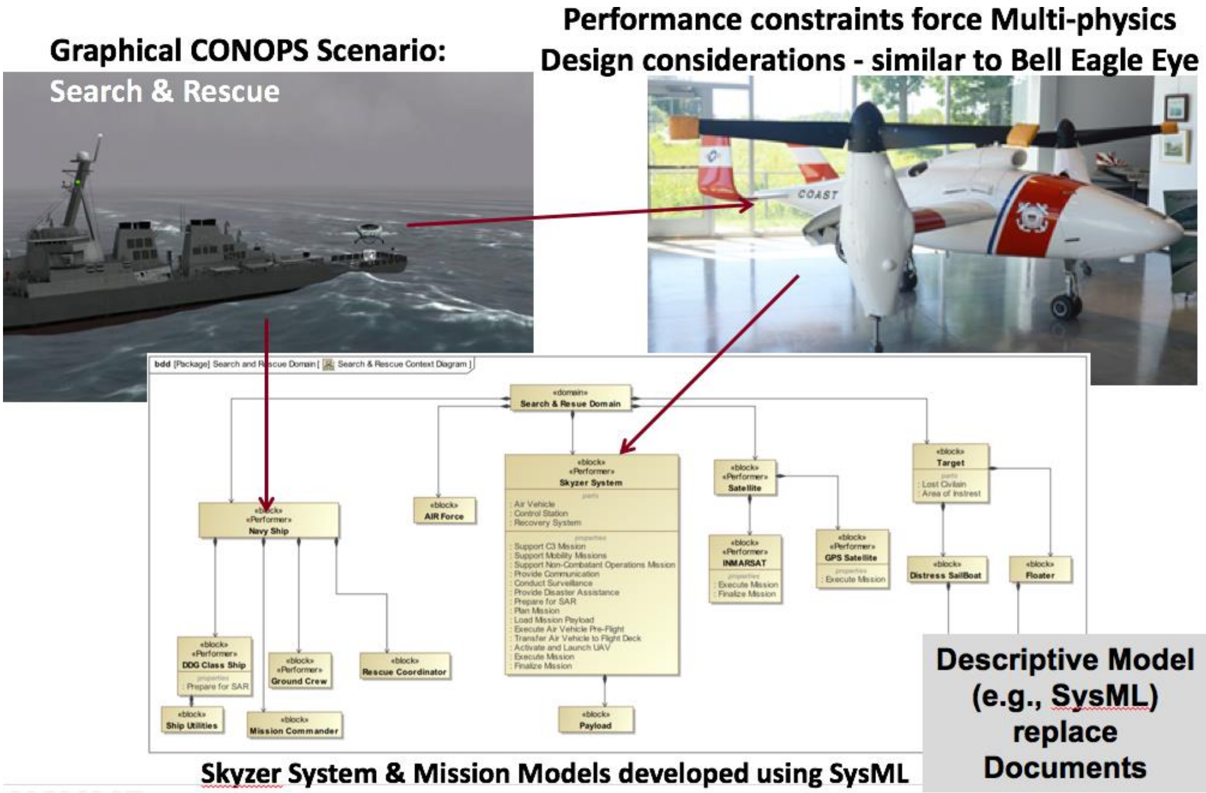

Figure 4. Graphical CONOPS for Skyzer UAV[4]

[4] NAVAIR Public Release 2019-443. Distribution Statement A – "Approved for public release; distribution is unlimited"

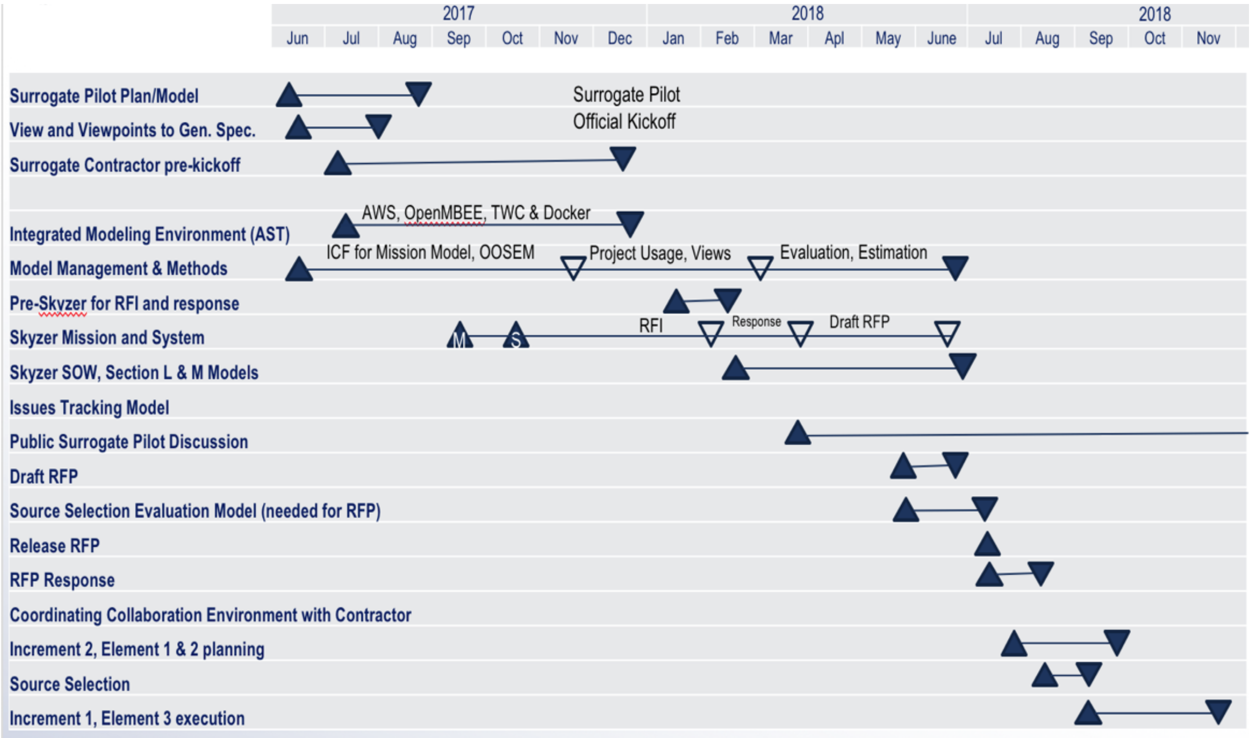

Figure 5. Time Line of Surrogate Pilot Experiments[5]

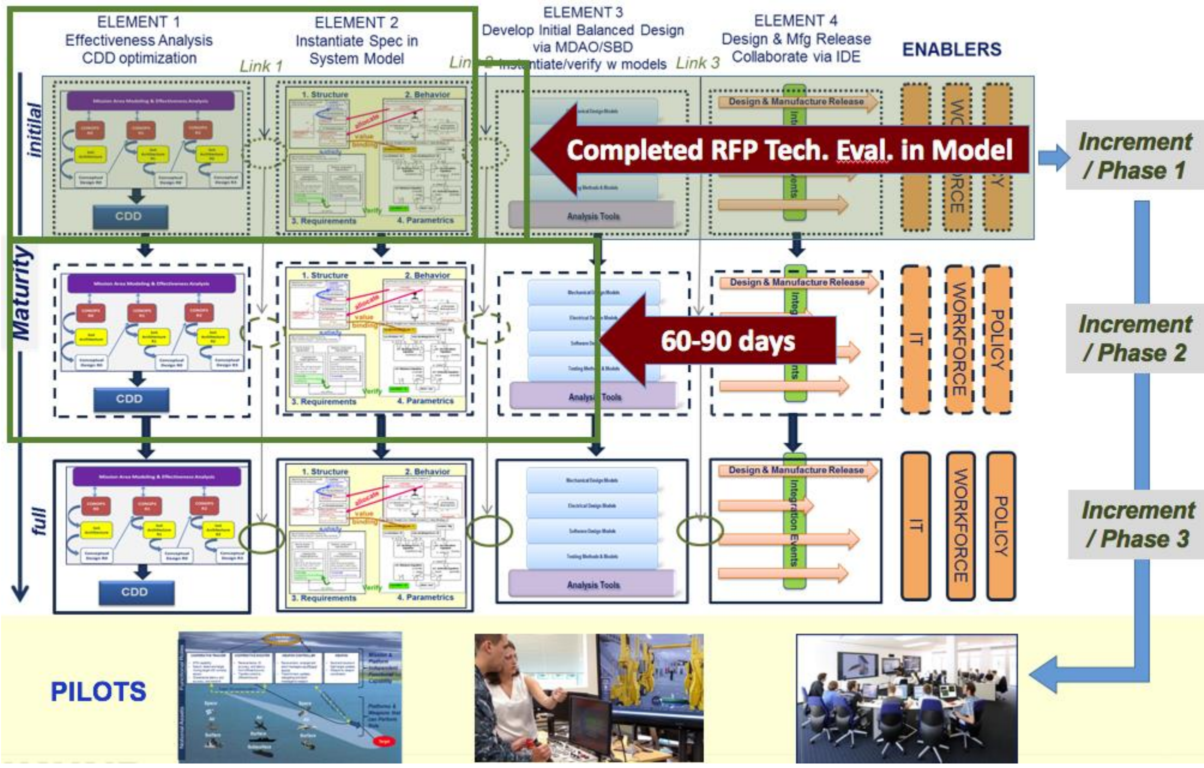

Figure 6. Transitioning from Phase 1 to Phase 2[6]

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[5] NAVAIR Public Release 2019-443. Distribution Statement A – "Approved for public release; distribution is unlimited"

[6] NAVAIR Public Release 2017-892. Distribution Statement A – "Approved for public release; distribution is unlimited"

NAVAIR has been reaching out to industry to engage in discussions about this new operational paradigm to acquisition since 2015. Industry has responded favorably about this change of direction. For example, industry initiated a new CONOPS of operations with organizations involved in the Aerospace Industry Association (AIA) working group [3]. The National Defense Industry Association (NDIA) Modeling and Simulation group which is looking at approaches for using digital engineering for competitive down select. In response, VADM Grosklags provided an overview of the SE Transformation at the NDIA Systems Engineering Conference in October 2017 [86]. On March 8, 2018, NAVAIR officially announced the SET as part of a larger Industry Request for Information (RFI), where industry was invited to six (6) hours of briefing material on the details of the SET [123], including details about the surrogate pilot experiments. In August 2018 NAVAIR conducted an industry review of the Acquisition System Reference Model (ASRM) to provide industry with the opportunity to make constructive comments on representation and content that will likely be provided as “System Model(s)” as GFI as part of future solicitations such as RFI or RFPs. We presented at NDIA Systems Engineering Conference in October 2018 and were approached by industry who wants to participate in the surrogate pilot; the use cases are being planned for Phase 2. At the two-day Model-based Ecosystem breakout session at INCOSE in January 2019, we briefed details about our surrogate experiments and use of OpenMBEE [138] as a foundational element of our AST and found out that Boeing has 40 programs and over 200 users using OpenMBEE, and Lockheed Martin also has many programs but plans to be part of the open-source community to advance OpenMBEE by developing the next version of the Model Management System (MMS) component of OpenMBEE.

It was announced during the presentation at the SET RFI Industry Day that the Surrogate Pilot experiments, models, generated specifications, results, and lessons learned would be shared with industry and government on the All Partners Network (APAN.org). APAN was setup and is managed by Defense Information Services Agency (DISA). DoD organizations can request their own groups, and NAVAIR has several groups for the SET. Some are internal for NAVAIR people and their contractors, but the Surrogate Pilot Group (https://community.apan.org/wg/navair-set/set-surrogate-pilot/) is open to the public with the proper registration in APAN. The Surrogate Pilot group captures weekly progress for the SET Surrogate Pilot in the Discussion threads, often with videos. We are sharing this with Industry and Government to solicit feedback and recommendations on the way we are proceeding in this pilot. Many of the lessons learned from this surrogate pilot are reflected in this report.

1.1 Objectives

The objectives for the research factor in NAVAIR’s evolving needs and priorities and look at the cross-cutting relationships associated with the research needs, as shown in Figure 7. We have been successful at the initial use and deployment of OpenMBEE as the experimental integrated modeling environment (IME) for an AST. The research needs expand on the prior research and include specific focus on technological aspects to address the prior research gaps in the context of the SET Framework. We summarize and organize in a manner used on RT-168/170 as use cases (UC) that cut across the evolving case studies as it relates to Figure 7.

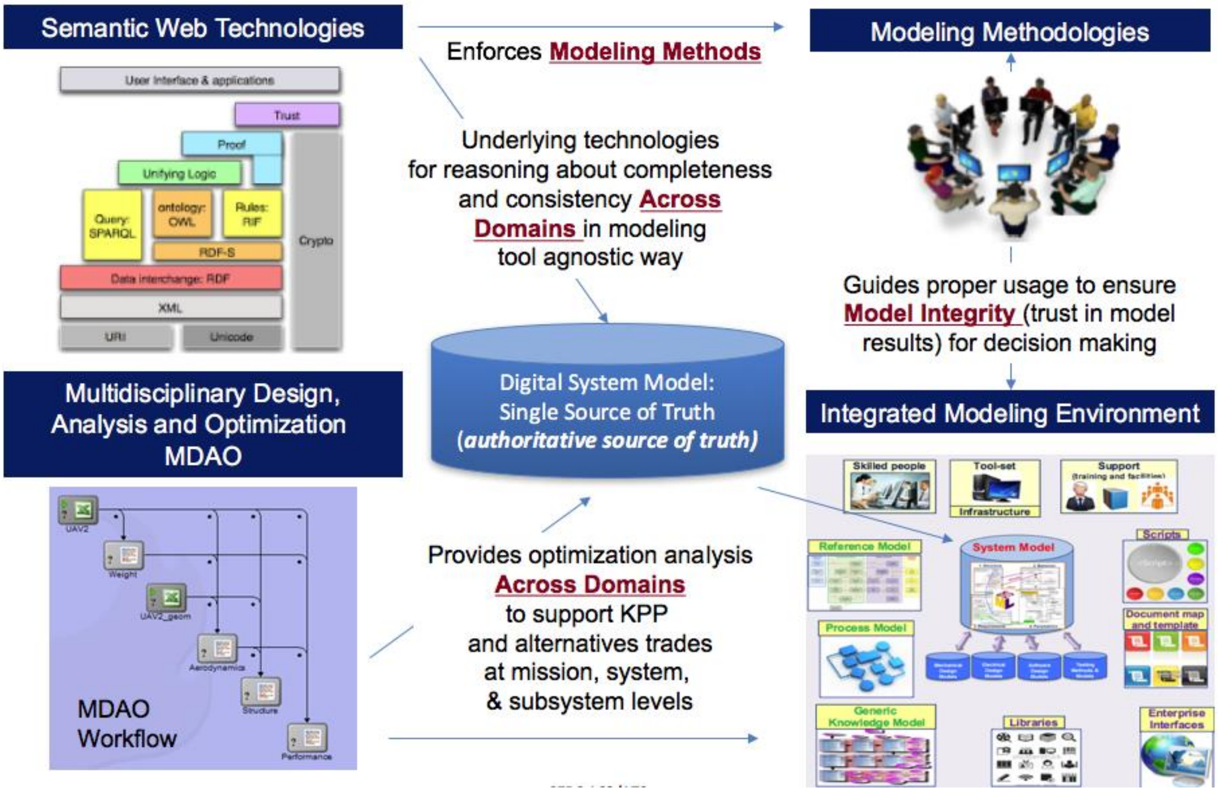

Figure 7. Cross-cutting Relationships of Research Needs

The use cases include, but are not limited to:

- UC00: Ontologies and semantic web technologies for reasoning about completeness and consistency across cross-domain model to achieve the notion of model integration through interoperability are enablers for an authoritative source of truth, tool-agnostic approaches to methodology enforcement and conformance that also support model integrity
    - Develop an initial architecture ontology represent interoperable ontologies to cover the Naval domains, with specific focus on NAVAIR using the Basic Formal Ontology as the upper ontology
    - Ontologies should focus on leveraging other work done in the Department of Defense such as the Joint Doctrine Ontology and US Air Force
    - Initial effort is focused on using ontology architecture to scope the identified need, enforce interoperability, creating common terminology across domains, and be an enabler for model-based systems engineering
    - Development of an architectural construct related to the Navy and DoD Ontology Suite, and associated pilots as represented in Figure 8; this was developed as a result of a Navy and DoD Ontology Workshop
- UC01: Multidisciplinary Design, Analysis and Optimization (MDAO) at the mission, system and subsystem levels, which provides a means for continual assessment of trades (i.e., analysis of alternatives) to support KPP assessment; this also relates to representations within system models
    - Applied to the Surrogate Pilot, for more elaborate uses of MDAO see CCDE efforts that are relevant to NAVAIR
- UC02: Integrated Modeling Environment (IME) in the context of the workflows, which has implications on both technologies and workforce development

- We are using an instantiation of NASA/JPL OpenMBEE as the experimental integrated modeling environment formalization of the AST, in the context of NAVAIR, but also in the context of one or more industry contractors
    - Model visualization from multiple perspectives including, but not limited to enabling different views relevant to different stakeholder (or due to particular access), reducing complexity, and analytical analysis
    - Methods for model modularization to ensure separation of concerns, classification, acquisition
    - Methods for creating and organizing Enterprise, Process, and Reference models
    - Understanding the operational paradigm between industry and government in the context of the SET Framework through MCE
    - Workflow analysis and representation relative to a program instantiation of tool suites from the IME
    - NOTE: cyber security and classification is not currently in the scope of this work, but is a candidate for investigation on a proposed follow-on research to RT-168
- UC03: Methodology for all of these technologies in the context of the IME workflows, such as:
    - Methods for system model
    - Methods for mission model
    - Methods for MDAO modeling
    - Methods for modularizing models to support constraints needed for developing an authoritative source of truth, which relates to many other use cases
    - Methods for model management
    - Methods for representing and organizing reference models, process models, discipline-specific models
    - Methods for developing and tracing capabilities measure to KPPs
    - Alternative approaches to improve modeling methods, which is fundamental to ensuring model integrity (strong relationships to UC02)
- UC04: Model-physics modeling, which is also supported by MDAO and approaches for assessing model integrity risks and uncertainty
- UC05: Representation to formalize research under RT-176 in models to support requirement verification and validation
- UC06: Experimentation and learning all prior defined research topics in the execution of the SET through unclassified pilot programs; this includes alignment with the SET Tasking and other research use cases with evolving pilot case studies (as described below)
    - A significant part of the summary for the experiments is provided in Section 2 rather than in Part II of this report
- UC07: Research into Enterprise Transformation to support governance and workforce development

All of these use cases will investigate continuing synergistic research to the extent possible with the US Army ARDEC, Semantic Technologies for Systems Engineering, and other potential SERC research that is aligned with the principles and concepts for the Systems Engineering Transformation as well as the ODASD(SE) Digital Engineering Strategy.

Level of Granularity	Thing	Attribute	Process	Information Entity
System	Weapons system Business system …	Dependability Safety Reliability		Requirement Specification Decision
Platform	Platform			
Organization				
Person Role				
(information-oriented)			Data Exchange Classification Guidance	Data, metadata, …
Material			Manufacturing (PLC)	
Physics	Sensor, …		Motion (Kinematics)	Sensor data Physics data …

Figure 8. Draft Navy and DoD Ontology Matrix Construct[7]

1.2 Scope

The scope for the research aligns the objectives as characterized by the use cases in Section 1.1. As reflected in Figure 1, the scope of these research task areas has expanded and continues to realign to the evolving prioritizes of the SET in the context of the surrogate pilot experiments, which have produced models, demonstrations and videos for NAVAIR-relevant examples that can help inform the workforce and other stakeholders. The objectives of the surrogate pilot involve understanding the methods, models, tools, collaboration technologies and process to execute, assess and refine the SET Framework in order to more fully characterize the Elements of SET. There are two perspectives as reflected by Figure 9:

1. Use cases about the objectives for the Skyzer experiments and associated environments:
   - Surrogate Pilot Use Cases characterize objectives for understanding the execution of the SET Framework
     - A non-exhaustive set of objectives for the surrogate pilot are characterized in the SET Surrogate Pilot Project Model; an automatically generated version of the model content (e.g., “document”) from this evolving model is provided in Appendix A
   - Collaboration in an AST Use Cases
     - The government side of the AST is being developed using the NASA/JPL OpenMBEE [138] and commercial modeling tools that is hosted on Amazon Web Services (AWS) server
     - The surrogate contractor side of the AST must be “integrated” with the government side of the AST
2. Use cases for the Skyzer Experimental System using AST, which involves the development of evolving models for:
   - Surrogate Project/Planning Model
     - Characterizes the objectives for the surrogate pilot and research

[7] NAVAIR Public Release 2019-443. Distribution Statement A – “Approved for public release; distribution is unlimited”

        - Discussed in more detail in this report in Appendix A
    - Project Planning for Skyzer
        - We would like to model this plan, but this was not viewed as a priority given our limited resources, and this is a more traditional document
    - Mission Model for Skyzer
        - Parts of mission model provided as GFI
        - Primarily associated with Element 1 of SET Framework
        - RFP release of Views generated using OpenMBEE DocGen are viewable on AWS
    - System Model for Skyzer
        - Parts of system model provided as GFI
        - Primarily associated with Element 2 of the SET Framework
        - RFP release of Views generated using OpenMBEE DocGen are viewable on AWS
    - Acquisition Model Skyzer
        - Primarily associated with boundary between Element 2 and Element 3 of the SET Framework
        - Models for the Statement of Work (SOW)
        - Provide criteria for source selection evaluation as model and provided to surrogate contractor as GFI
        - Source selection technical evaluation criteria
        - RFP release of Views generated using OpenMBEE DocGen are viewable on AWS
    - Surrogate Contractor System model for Skyzer
        - Provided as a SysML model as the RFP response
        - Model objectives provided hyperlinks to multi-physics models and analyses for discipline-specific tools (e.g., computation fluid dynamics)
        - Surrogate contractor to assess, refine and extend GFI system model
        - Primarily associated with Element 3 of the SET Framework
    - Surrogate Contractor Design models for Skyzer
        - Design models addresses aspects of multi-physics
        - Primarily associated with Element 3 and Element 4 of the SET Framework, which were not started during Phase 1
    - View and Viewpoints for DocGen and other Libraries

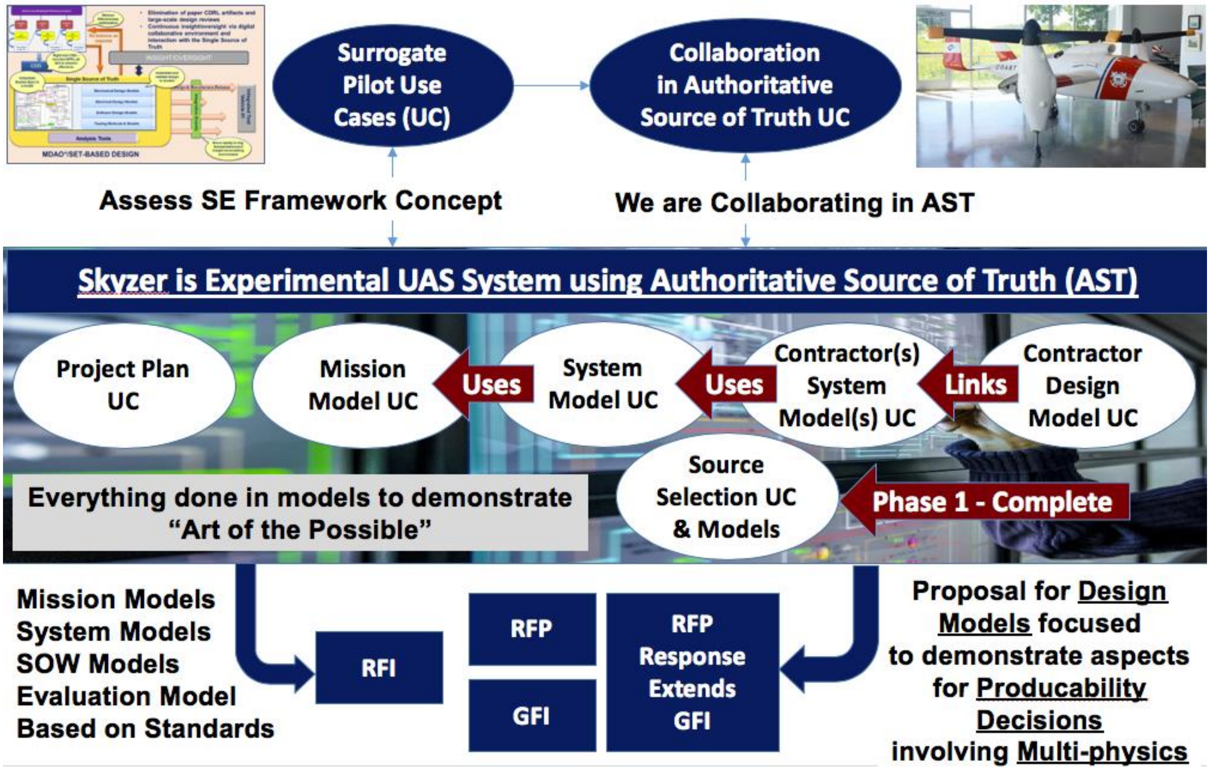

Figure 9. Use Cases for Surrogate Pilot and Experimental System (Skyzer)[8]

In order to run the surrogate experiments, we needed to have an IME for the government elements that are part of a broader AST as shown in Figure 10. The capabilities at a minimum must support modeling, model management, collaboration through web-based browser to view the information generated from the model. This is clearly an important capability and it is one of the six SET Functional Areas as shown in Figure 1. For NAVAIR programs this is more difficult due to the needs for managing security and access to potentially classified information. For the surrogate pilot, we wanted to use an environment to demonstrate the art-of-the-possible, and therefore we selected OpenMBEE. An early challenge with OpenMBEE was the installation process. Our research team developed several Docker configurations for script-based deployment of OpenMBEE that enables the use of the Model Development Kit/DocGen in conjunction with the Model Management System (MMS) and View Editor. The IME for the AST as shown below includes:

- Docker mechanism for easy deployment of OpenMBEE
  - Docker provides a mechanism to install OpenMBEE with a single script, and this has allowed us to deploy OpenMBEE on AWS, at Stevens, at Georgia Tech, and at the Surrogate Contractor site; this approach allows us to not only provide models at GFI, but also provide the exact environment that we used to construct the GFI
  - Deployed mission models, system model, SOW, and evaluation model views to the AWS OpenMBEE MMS
- Developed the information for the Request for Proposal (RFP), including:
  - Skyzer Mission model
  - Skyzer System model

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- Skyzer Mission views created by OpenMBEE Model Development Kit (MDK)/DocGen
    - Skyzer System views created by DocGen
    - Skyzer Statement of Work (SOW)
    - Source Selection evaluation model
    - Source Selection evaluation views created by DocGen
    - Surrogate Contractor created models for the RFP response, which provided links to other type of discipline-specific models (e.g., Computational Fluid Dynamics [CFD])
- All models stored in the Teamwork Cloud
- Any NoMagic Client (e.g., MagicDraw or Cameo System Modeler) can access the models if the user has the appropriate access rights

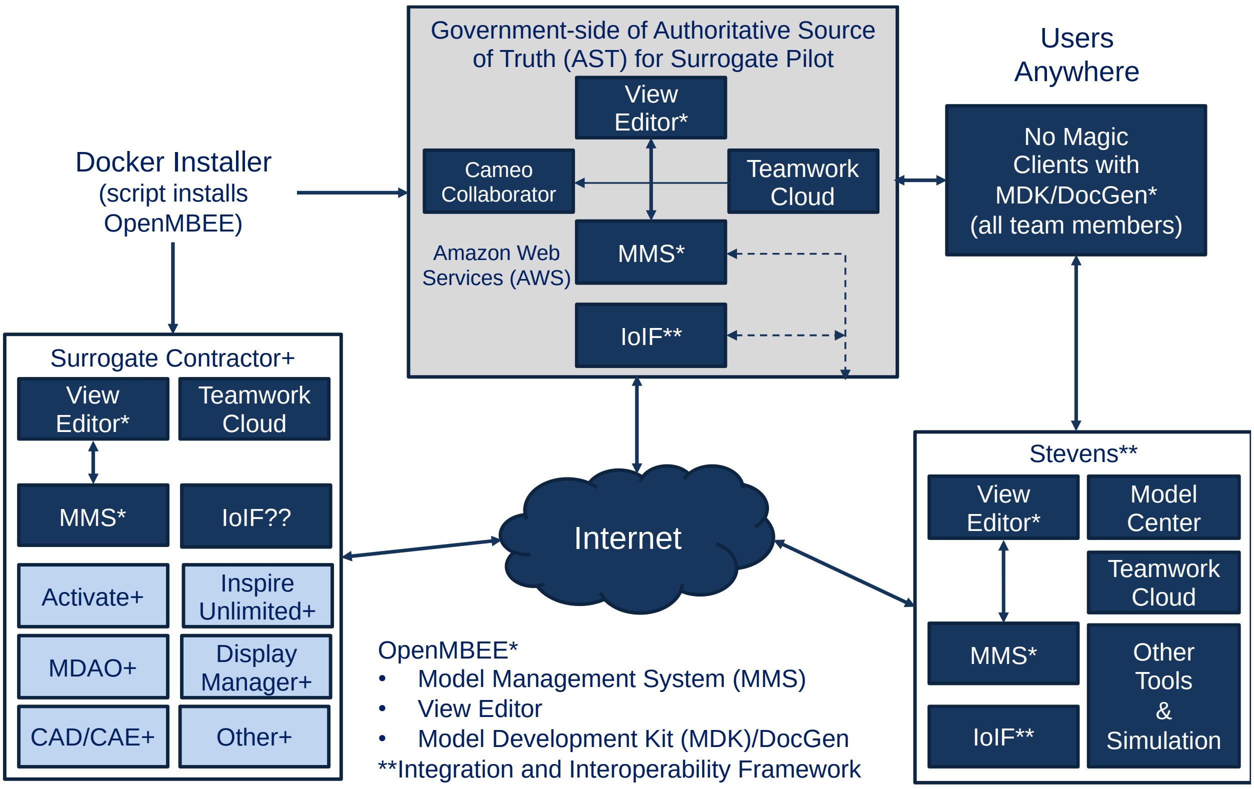

Figure 10. Elements of Authoritative Source of Truth[9]

As shown in Figure 11, we developed operational models and user capabilities, which are primarily defined in the Skyzer Mission Model. The mission model(s) provides inputs that are captured in an "Initial System Model" that characterizes the "requirements" in the Skyzer System Model. The Phase 1 Skyzer System Model was developed by our Georgia Tech collaborator. These Skyzer Mission and System models provide the basis for the RFP that was refined and elaborated by the surrogate contractors during source selection into a "Final System Model." We are simulating this concept during the pilots. Notionally, Figure 11 shows the related alignment to the four Elements 1, 2, 3, & 4 with the focus of formalizing the use of models. A non-exhaustive set of objectives for the surrogate pilot are characterized in the

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SET Surrogate Pilot Project models; an automatically generated "document" using OpenMBEE Model Development Kit (MDK)/DocGen is continuously generated from this evolving model that is provided in Appendix A. OpenMBEE DocGen is also used to generated stakeholder-relevant views [64] of the Skyzer Mission, System, SOW, and Technical Evaluation criteria and have been synchronized to the OpenMBEE environment on an AWS server that is shared with the entire team, and is also viewable to the public.

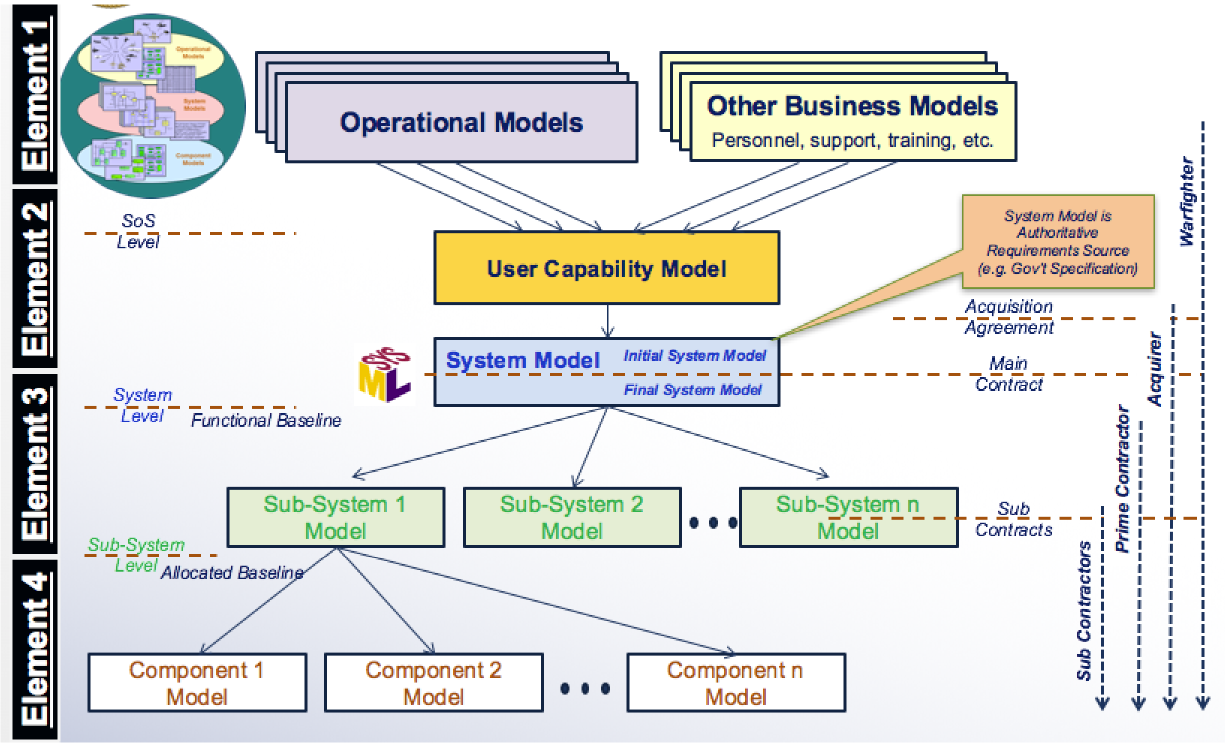

Figure 11. Characterizes the Boundary of Models between Government and Industry[10]

The research approach uses experimentation in evolving pilot project scenarios to help inform the workforce, as well as create reference models as examples to exemplify best practice methods. We demonstrated concepts that have never been attempted by NAVAIR. The inherent philosophy was to attempt to develop everything in the Phase 1 deep-dive using models; one may not normally want to build a model for everything, but we did look to model most things to show it could be done, to provide examples, and to explain the benefits, issues or challenges associated with the development of such models. For example, we found the development of the Technical Evaluation Criteria (normally Section L of the SOW) to be extremely valuable, because it eliminated many typical document-based requirements about form, and instead focused on functional information that is captured directly in models that should be provided by responders to the RFP as models.

There are many questions that have been answered, but also additional questions that have surfaced related to the execution of the SET Framework in Phase 1. We did not address all of these during the surrogate pilot, but reflect on some of the broad needs, several that have been investigated during Phase 1. Appendix A formalized many of the questions in terms of

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objectives in a model. The following is a high-level list of objectives, with some information on status, and additional needs for Phase 2:

- Simulating Mission Engineering and Analysis (Element 1) and System modeling (Element 2) prior to contract award; this is under consideration for Phase 2
  - Developed one mission use case in the deep dive for Search and Rescue for Phase 1
  - Need to start earlier with Mission Needs and include more mission use cases (e.g., Launch and Recovery from ship, Communication with Ground)
- Formalization/synthesizing a "specification" from models for RFP and methods for providing models to contractor
  - Using OpenMBEE DocGen, and also viewable using OpenMBEE View Editor on AWS
- Simulating "Execution" of Oversight / Insight in AST per SET Framework and capturing abstractions of recommended or best practice processes in potentially heterogeneous environments (Elements 3 & 4)
  - Ongoing after simulation of contract award following Source Selection
  - Created digital signoff model element as part of the source selection technical evaluation criteria, which is embedded within the surrogate contractor RFP response
- Developing and assessing the use of objective measures for evaluating evolving design maturity, while assessing the reduction of risk and uncertainty
  - Ongoing after simulation of contract award following Source Selection
  - Created digital signoff for System Engineering Technical Review criteria as means to provide a transformation from Contract Data Requirements Lists (CDRLs), which are embedded in the contractor models
- Simulating feedback back to mission engineering caused by specified objectives for unachievable KPP
  - Being simulated as part of Source Selection for one KPP
- Simulating approach for "faults in specification/model" detected after contract award to look at the potential needs for a new paradigm referred to as model-based acquisition
- Simulating source selection and investigating if it is possible to use dynamic simulations and V&V as part of the source selection process and evaluation criteria
  - Developed an Evaluation Model that is GFI as a supplement to Section L of the SOW, which calculates using the Cameo Simulation Tool kit margins for the KPPs specified in the mission model
- Working with contracts/legal to get agreement on what a "specification" would or can be, while helping to understand potential needs to change acquisition policy
  - Developed example models for SOW and Technical Evaluation Criteria
  - Provide examples for model-based contracting and digital approaches to traditional concept of Contract Data Requirements List (CDLS) prior to contract award
- Methods for modularizing model used to "generate specification" and for sharing digital models while addressing access needs such as security
  - Demonstrated methods for modularization specification using Project Usage mechanism, and corresponding Views that are used by DocGen

- Need to define better methods for Model Management, which is a priority use case for Phase 2
- Assessing how or if we can use an ontological representation of the Systems Engineering Technical Review (SETR) guide and checklist that NAVAIR uses? And, how will we make recommendations for its evolution in the context of MCE
    - Part of Element 3 in Phase 1 briefly shows a few examples for how models can subsume SETR criteria using Digital Signoffs
- Use of Multidisciplinary Design, Analysis and Optimization (MDAO)
    - Surrogate Contractor applied MDAO using ModelCenter for analysis of UAV design
    - Need more examples on the Government side to apply MDAO early as part of Mission Needs analysis

1.3 Collaborative Research Synergies

NAVAIR is also involved in synergistic collaborative efforts with ARDEC and the Digital Engineering (DE) Working Group led by the Office of Deputy Assistant Secretary of Defense for Systems Engineering (ODASD(SE)). We are working to align the research, to the extent possible, with the five DE Transformation goals [68] [193] that include:

- G1. Formalize the development, integration and use of models to inform enterprise and program decision making.
- G2. Provide an enduring authoritative source of truth.
- G3. Incorporate technological innovation to link digital models of the actual system with the physical system in the real world.
- G4. Establish a supporting infrastructure and environment to perform activities, collaborate and communicate across stakeholders.
- G5. Transform a culture and workforce that adopts and supports Digital Engineering (DE) across the lifecycle.

As is reflected in Figure 12, many of the research topics under investigation by the SET align with the DE Transformation goals. In addition, the mapping in Figure 12 shows that the research areas have significant overlap with some of the goals. This means that in order to achieve some of the goals, it will be necessary to have successful research outcome across many research areas.

Future Research Areas	**G1.** Formalize the development, integration and use of models to inform enterprise and program decision making.	**G2**. Provide an enduring authoritative source of truth.	**G3**. Incorporate technological innovation to link digital models of the actual system with the physical system in the real world.	**G4**. Establish a supporting infrastructure and environment to perform activities, collaborate and communicate across stakeholders.	**G5**.Transform a culture and workforce that adopts and supports DE across the lifecycle.
Cross-discipline integration of models to address the heterogeneity of the various tools and environments using semantic technology	X	X	X	X	X
High Performance Computing (HPC) advancements such as; 1) supporting organizing and analyzing "Big Data" and 2) being able to program in parallel to take advantage of HPC capabilities, are needed to support the DE effort	X	X	X	X	
Model integrity to ensure trust in the model predictions by understanding and quantifying margins and uncertainty	X	X	X	X	X
Modeling methodologies that can embed demonstrated best practices and provide computational technologies for real-time training within digital engineering environments	X		X	X	X
Model composability to understand the possibilities, constraints and rulesets for composition of multiple models	X		X		
Human-model task allocation to understand what activities are best performed by human decision makers and what can effectively be automated or augmented with model intelligence					X
Workforce development to understand what is needed to educate model developers, users and decision makers to work in a DE environment					X
MCE acquisition to understand the needed changes to acquisition and security when developing in the new DE environment	X	X		X	X

Figure 12. Future Research Areas Mapped to Goals of Digital Engineering Transformation Strategy

We are also fostering bi-directional sharing of research interests and results with our US Army ARDEC sponsors. We are collaborating in several MCE-related efforts to provide the opportunity to leverage and share with the Open Collaboration Group for MBSE and OpenMBEE [138], Semantic Technologies for Systems Engineering (ST4SE) initiative, DoD Digital Engineering Strategy, the Aerospace Industry Association (AIA) on Concept of Operations (CONOPS) for Government and Industry collaboration through MBSE [3], the National Defense Industry Association (NDIA) Modeling and Simulation & NDIA System Architecture groups and INCOSE who are coordinating working groups to investigate approaches for using Digital Models for competitive down select.

1.4 ORGANIZATION OF DOCUMENT

Part I provides an overview of the research task.

Section 1 provides an overview of the context for the needed research, objectives, expanded scope and organization of this report.

Section 2 provides a summary of the research results, surrogate pilot experiments and lessons learned, research-related events, and deliverables.

Part II describes the details for each research Use Cases (UC) and other collaborative research efforts.

Section 3 describes use case UC00 including challenges of cross-domain model integration where we are investigating the use of ontologies and semantic web technologies approach for interoperability.

Section 4 describes use case UC01 and the examples, demonstrations and methods for Multidisciplinary Design, Analysis and Optimization.

Section 5 describes use case UC02 that discusses our approach for an Integrated Modeling Environment (IME) using OpenMBEE with specific focus on creating and collaborating in an Authoritative Source of Truth (AST) for the surrogate pilot experiments. Much of this information was also introduced and covered in Section 2.

Section 6 describes use case UC03 that discusses developments and demonstrations for focused around methods that align with technologies in the context of the IME workflows, for mission, system, MDAO, and model modularization.

Section 7 discusses use case UC04 that investigates model-physics modeling, MDAO and model integrity which is also supported by MDAO and approaches for assessing model integrity risks and uncertainty.

Section 8 discusses use case UC05 that investigates the development of SysML representations to formalize the Monterey Phoenix (MP) research under RT-176 to support requirement verification and validation, and one example of applying MP to a surrogate pilot mission scenario.

Section 9 discusses use case UC06 for experimentation and learning in the context of surrogate pilot focused on the execution, assessment and refinement of the SET Framework, which is also discussed in Section 2.

Section 10 discusses use case UC07, which is the research into Enterprise Transformation to support governance and workforce development.

Section 11 discusses other SERC research synergies with organizations like the US Army ARDEC, Semantic Technologies for Systems Engineering, OpenMBEE and Open Collaboration Group for MBSE, Aerospace Industry Association, National Defense Industry Association Modeling and Simulation, and International Council on Systems Engineering (INCOSE) model-based ecosystem.

Section 12 provides conclusions with a brief summary of the planned next steps.

Part III describes the Surrogate Pilot Project Model.

Appendix A includes the automatically generated view from the SE Transformation Surrogate Pilot Project model.

Appendix B includes research by research collaborator on semantic web technologies that have resulted in number of recent conference publications.

Appendix C includes an article that was submitted to INCOSE *Insight on Implementing a Decision Framework in SysML Integrating MDAO Tools.*

2 RESEARCH SUMMARY, EVENTS AND DELIVERABLES SUMMARY

This section provides a summary of the research results, lessons learned, research-related events, and deliverables. We are not including a historical perspective of prior research in this report. We have shifted focus to the recent developments in 2018 for the SET, with specific focus on the research addressed through the surrogate pilot results and the lessons learned. The technical reports RT-141 [25] and RT-157 [26] provide a comprehensive summary and historical perspectives leading up to the SET of the two first phases of the research: 1) global scan of state-of-the-art in MCE, and 2) initiating the NAVAIR SE Transformation.

Additional details are in Part II of this report, which includes a summary of the use cases which characterize the cross-cutting research. Appendix A has been automatically generated from the SET Framework Surrogate Project model using OpenMBEE DocGen, which provides details on the surrogate pilot plan and objectives. In addition, Part II describes research synergies leveraged from the ARDEC research under RT-168 [28] that are still relevant to SET (e.g., MDAO, Decision Framework, IME), and the surrogate pilot.

2.1 SURROGATE PILOT EXPERIMENTS RESULTS OVERVIEW

This section provides details on the key results of performing the surrogate pilot experiments under Phase 1. The reason for characterizing these results as key comes from sponsor responses to the results and knowledge gained from our presentations of this information at working sessions and to the Navy system commands (SYSCOMs); key results summarized in this section include, but are not limited to:

- Example of an implementation of an AST as shown in Figure 10 comprised of multiple modeling environments
- Understanding of View and Viewpoints used by DocGen to produce stakeholder-relevant views of models that are editable in the OpenMBEE View Editor
- Project Usages model linking capabilities that provides for an AST to link Mission, System, and Contractor descriptive SysML models
- How the contractor RFP response links SysML models to discipline-specific design and analysis models
- Digital signoff using editable model objects in the View Editor as a means for transforming CDRLs and performing source selection technical evaluation
- Significant detail on the contractor design and analyses provided as part of the RFP response using discipline-specific models for multi-physics analysis and design

This section provides the most coverage for the research use cases ***UC02: Integrated Modeling Environment (IME)***, **UC03: Methodology for all of these technologies in the context of the IME workflows*, UC06: Experimentation and Learning for Research Topics in the Execution of SET, and UC04: on how Multi-physic modeling was incorporated into the Surrogate Pilot***; this information has been moved to Part I of this report to provide early focuses on the surrogate pilot experiments. Much of this information is a refinement from information that is captured in the Surrogate Pilot Group of APAN (APAN.org @ https://community.apan.org/wg/navair-set/set-surrogate-pilot/). The APAN group and discussion threads provide a project journal, which helped to construct a lessons learned summary.

Phase 1 of the surrogate pilot focused on moving through the SET Framework concepts, shown in Figure 1, Elements 1 through Element 4 as quickly as possible. We defined only three mission scenarios to form the basis for the Skyzer Mission model associated with Element 1 of SET Framework. We further reduced the scope to one mission scenario, maritime search and rescue, for the refinement of the mission requirements that are captured in a Skyzer System model for Element 2. These two models provide the basis for the deep dive that includes multi-physics designs concepts for the RFP response and Element 3. An unexpected benefit in this process was that we formalized, in models, much of the process associated with SOW, RFI, RFP and source selection, which is effectively at the boundary between Elements 2 and 3.

The surrogate contractor also delivered an RFP response that extended the Government Furnished Information (GFI) for the mission and system models in a descriptive SysML model as reflected in Figure 9. The SysML model includes links to discipline-specific models that characterize multi-physics analyses and a preliminary air vehicle design as shown in Figure 13. This level of detail is generally not provided to NAVAIR prior to contract award. The surrogate experiment has demonstrated that models requested as part of an RFP response provide evidence that SMEs from NAVAIR would be substantially more well informed about analyses and system design prior to contract award; the approach used on the surrogate pilot provides more design information earlier, which should be able to reduce time to the initial test vehicle or system; this is a key desire and objective of the NAVAIR sponsors.

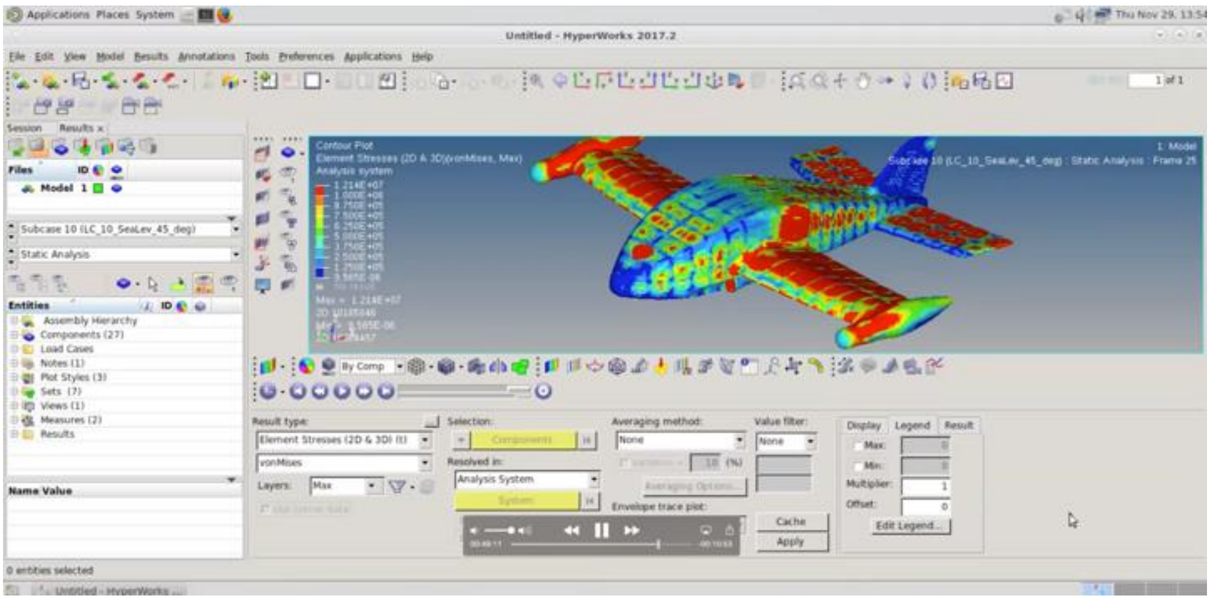

Figure 13. Multi-physics Analysis and Design Provided in Request for Proposal Response[11]

We also formalized the RFP source selection process as a model and performed the Technical Evaluation directly in the View Editor using Digital Signoffs. These digital signoffs are model objects that can be edited and saved in the View Editor, and then they get synchronized back into model as part of the AST. Use cases also demonstrated how to embed Digital Signoffs in a model, where the signoff can occur in the View Editor (i.e., web browser). The digital signoff is associated with criteria that is typically required at a formal review such as System Requirement Review (SRR); this demonstration provides an approach for eliminating

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Contract Data Requirement List (CDRLs), which define documents to be delivered. Instead the digital signoffs are directly associated with evidence that in in the surrogate contractor model[12]. An example of a digital signoff is shown Figure 14; this is an image of the View Editor that provides a View (see section 2.3) of information generated from the model. A SME could enable edits, add a risk and then add approval status. The digital signoff is template-based, which means that digital signoffs can have different columns, such as multiple signoffs.

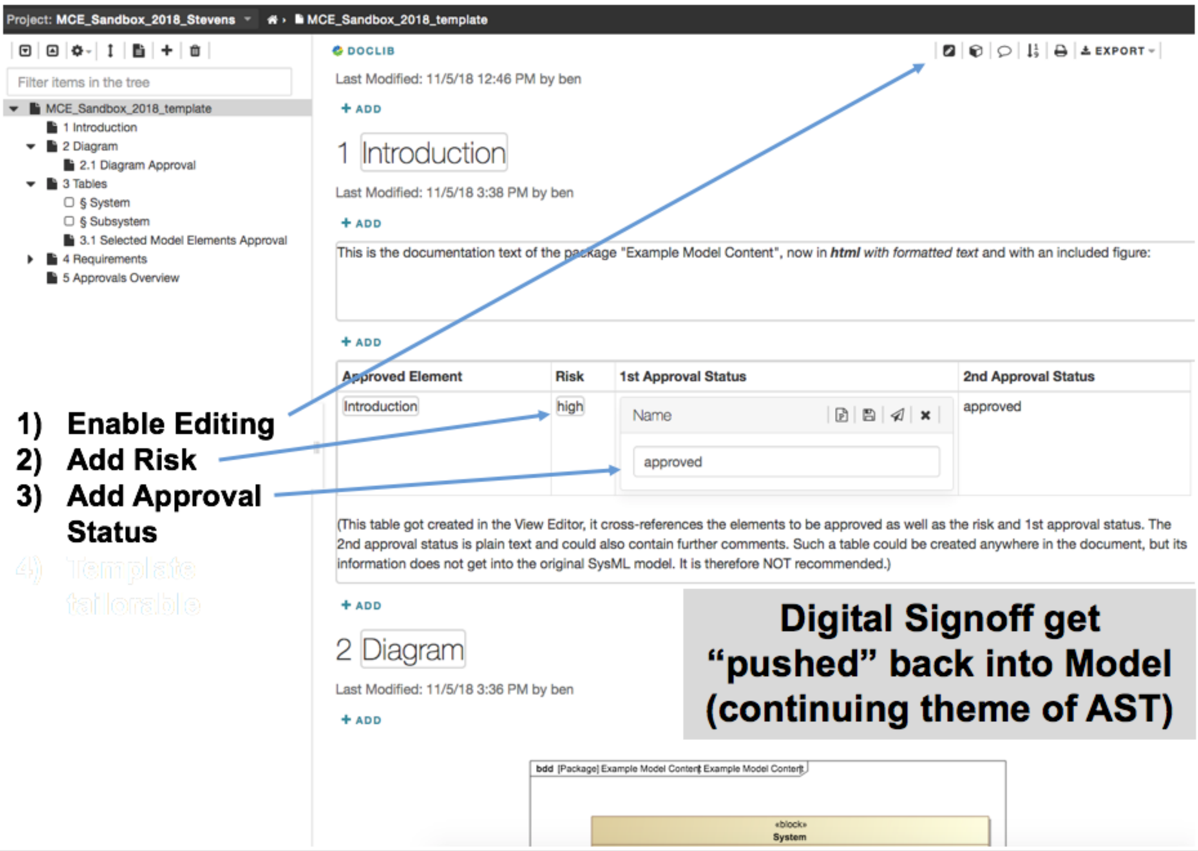

Figure 14. Transform CDRLs and DIDS using Digital Signoff in Model Through View Editor[13]

The surrogate pilot did demonstrate how the government and surrogate contractor could collaborate in an implementation of an AST, which is reflected in Figure 17. We demonstrated how to create linkages between system models to discipline-specific models such as Computational Fluid Dynamics (CFD). The surrogate contractor did provide one example for Multidisciplinary Design, Analysis and Optimization (MDAO), which was an extension from information provided in Government System Model. The surrogate contractor model also used an Evaluation Model provided as part of the RFP to calculate margins for the KPPs for the requirements from the Skyzer Mission Model.

2.2 OUTREACH

NAVAIR decided to make the Surrogate Pilot Group on APAN open to government, selected industry, and selected academia individuals as an approach to share the results and to solicit

[12] See Video: https://community.apan.org/wg/navair-set/set-surrogate-pilot/m/documents/252732

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feedback. The group currently has over 190 members, and provides discussion threads about many of the topics discussed in this report such as:

- NAVAIR SET Surrogate Pilot Discussion Thread – main thread summarizing weekly events, discussions and status, with links to models, presentations and videos
- Collaboration Environment for Authoritative Source of Truth
- Model Management Methods and Practices, includes Project Usages
- Source Selection using Models
- Ontologies and Semantic Technologies
- Transformation of CDRL/DIDs through Model Artifacts and Digital Signoff in AST
- OpenMBEE Resources and Models
- Issue Tracking in Surrogate Pilot
- Releases

The APAN Surrogate Pilot Group also has other information and resources, such as:

- Files that contain:
  - Models (e.g., mission, system, etc.)
  - DocGen Generated Views from Models
  - Information on Installing OpenMBEE with Docker
  - Presentations
  - Videos (e.g., of the weekly meetings and deep dive sessions)
- Wiki with links to resources, such as:
  - Ontologies for Systems Engineering
  - Surrogate Pilot SysML Modeling Guidelines
  - NASA/JPL Systems Engineering Cookbook
  - Views and Viewpoints

2.3 View and Viewpoints used by DocGen to produce stakeholder-relevant views of models that are editable in the OpenMBEE View Editor

The concept of View and Viewpoints has been around for more than a decade, but the specific implementation embodied in the NASA/JPL implementation of the Model Development Kit (MDK) and DocGen provide a concrete mechanism for people to better understand how DocGen can produce stakeholder-relevant views of models that are editable in the OpenMBEE View Editor (i.e., web browser). This scenario illustrates that working examples are important for understanding new technologies.

The approach for developing the mission model for Phase 1 is based on a Navy standard. We are working to align it with the ASRM during Phase 2. This approach demonstrates that modeling can be used and comply or be aligned with existing standards that traditionally have been document-based. We have a View and Viewpoint hierarchy that extracts information from the Skyzer Mission model to “generate a specification” that can be viewed in the View Editor, or also printed out. A portion of the mission model View and Viewpoint hierarchy shows the basic elements, as shown in Figure 43 that can be included within an overarching document, which includes:

- Document – the overarching model element
  - Document can include other documents, which also provides another level of modularization and support for reuse

- View (there can be one or more views in a document – these map to headings in a document)
- A View uses the Exposes relationship to associate the View with some element in a SysML model (e.g., Package, Diagram, etc.)
- View conforms to a Viewpoint
- Viewpoint in MDK is a special language created out of a profiled activity diagram that can collect, filter, sort, and then produce a document through a DocBook standard

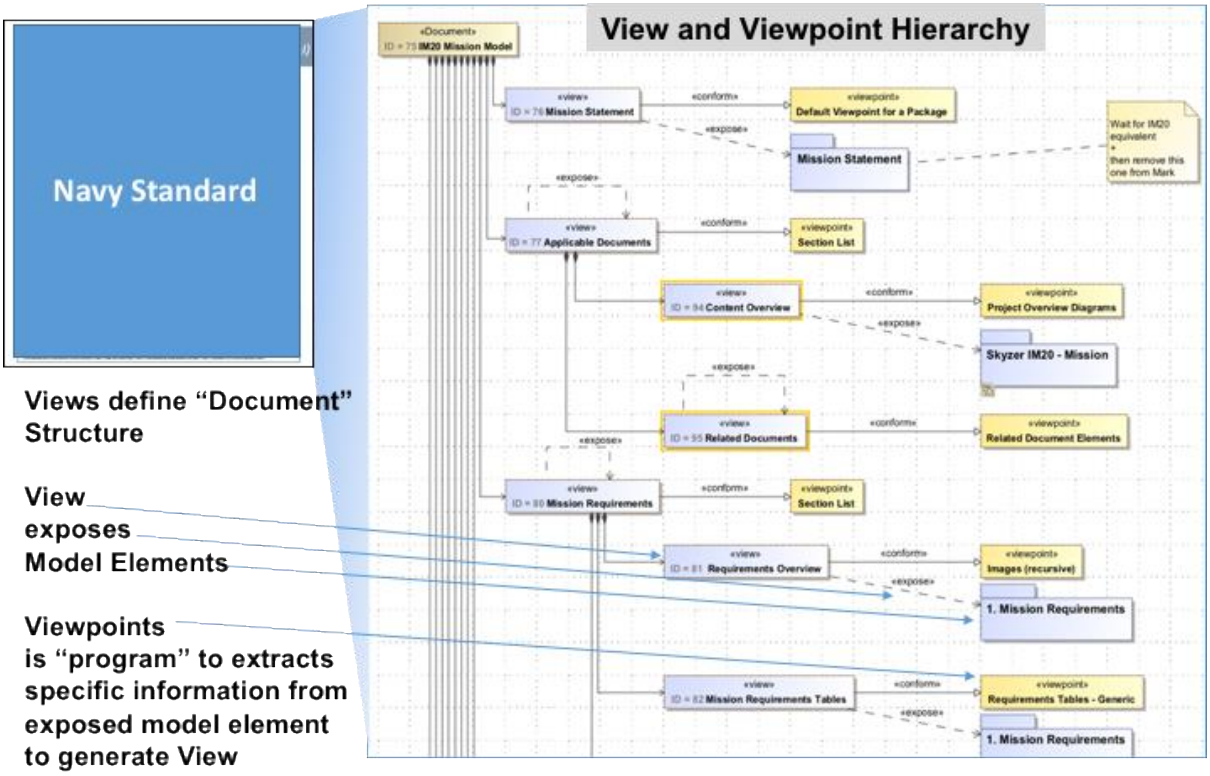

Figure 15. View and Viewpoints for Mission Model[14]

A document assembled from a number of Documents or Views can be generated into DocBook, which can then be generated into PDF, Word, HTML, and other formats. These Views can also be synchronized into the OpenMBEE Model Management System (MMS). The View Editor can then be used to view the generated specification as shown in Figure 16; in addition, it can export (generate) into Word, PDF, and HTML. The View Editor also allows for editing and updating a generated view that can also be pushed back into the MMS, as well as back into the model (for certain types of model elements). NASA/JPL open-sourced the OpenMBEE capabilities in an attempt to encourage companies to incorporate the capabilities into their offerings. Version 19 of the NoMagic tools provides DocGen capabilities and the upcoming Cameo Collaborator is going to provide some capabilities, like the View Editor, for editing model objects in a web browser.

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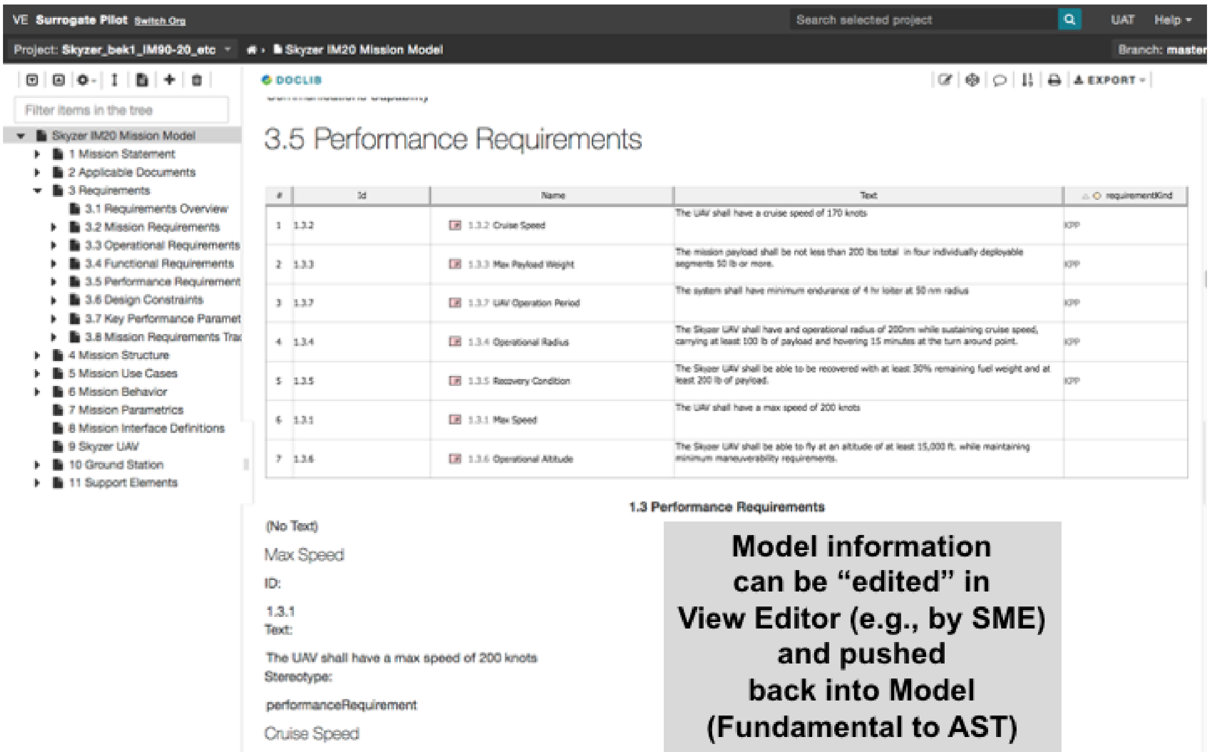

#	Id	Name	Text	requirementKind
1	1.3.2	1.3.2 Cruise Speed	The UAV shall have a cruise speed of 170 knots	KPP
2	1.3.3	1.3.3 Max Payload Weight	The mission payload shall be not less than 200 lbs total in four individually deployable segments 50 lb or more.	KPP
3	1.3.7	1.3.7 UAV Operation Period	The system shall have minimum endurance of 4 hr loiter at 50 nm radius	KPP
4	1.3.4	1.3.4 Operational Radius	The Skyzer UAV shall have and operational radius of 200nm while sustaining cruise speed, carrying at least 100 lb of payload and hovering 15 minutes at the turn around point.	KPP
5	1.3.5	1.3.5 Recovery Condition	The Skyzer UAV shall be able to be recovered with at least 30% remaining fuel weight and at least 200 lb of payload.	KPP
6	1.3.1	1.3.1 Max Speed	The UAV shall have a max speed of 200 knots	
7	1.3.6	1.3.6 Operational Altitude	The Skyzer UAV shall be able to fly at an altitude of at least 15,000 ft. while maintaining minimum maneuverability requirements.	

Figure 16. Example: View Editor shows Skyzer Mission Model View[15]

2.4 Integrated Modeling Environment and Elements of the Authoritative Source of Truth

Figure 10 reflects that the AST is actually comprised of one or more nodes. For example:

- Government-side of the AST holds the Skyzer Mission, System, and SOW models and views on an AWS server with OpenMBEE and Teamwork Cloud
- Surrogate Contractor AST node holds the refinement of the Skyzer System models, but includes OpenMBEE, Teamwork Cloud and other design-specific modeling tools
- Stevens AST node provides another example of part of the AST; this is notionally similar to another contractor that might be involved in a program, but be contracted to support different mission requirements
- Any contractor may also have linkages to any of their subcontractors, which would extend the AST as a type of tree or graph

We are currently working to formalize the linkages and access mechanism from descriptive models such as SysML to discipline-specific analyses such as Computational Fluid Dynamics and topology optimization as reflected in Figure 17. We want to demonstrate the use cases for linking these types of analyses back to the Government Skyzer System and Mission requirements. This is part of the Phase 1 effort needed for Element 3.

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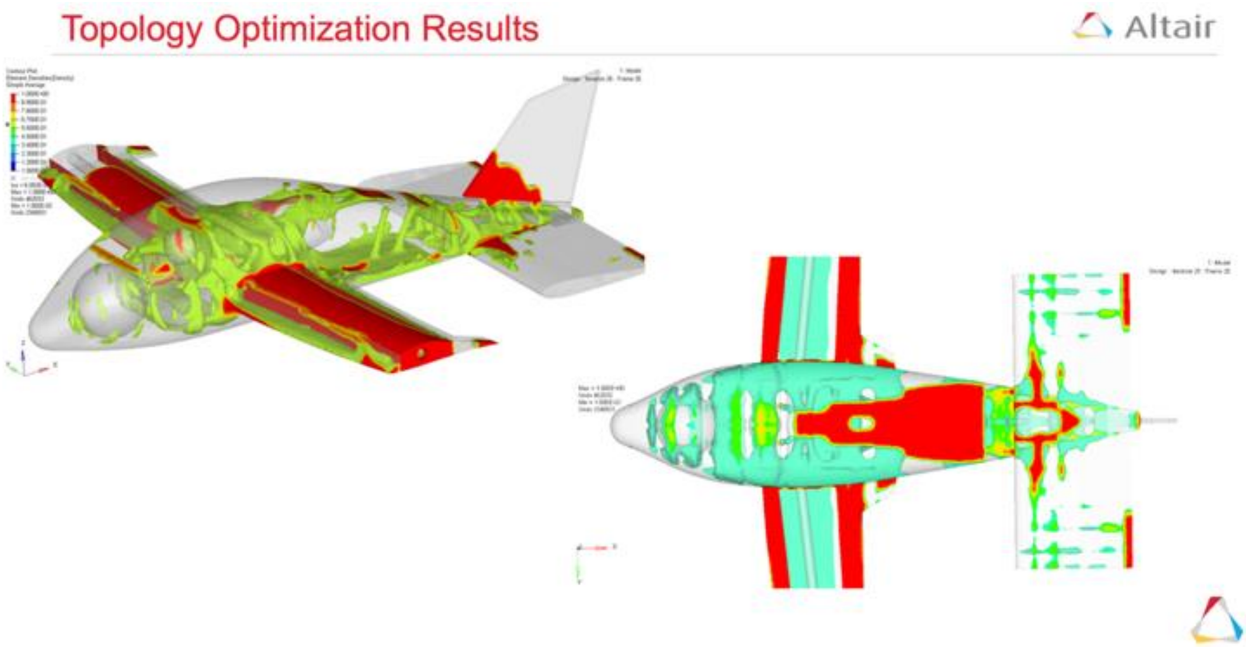

Figure 17. Surrogate Contractor Topology Optimization Analysis[16]

2.5 PROJECT USAGES FOR MODEL MODULATION METHOD

Project Usages is an approach for modularizing and reusing different models. Project Usages are similar to "include" mechanisms for software languages like C++ or called an "import" for languages like Python. Project Usages allows a model to be included into other models as shown in Figure 18. The creator of the used model can restrict visibility to Packages within that model when it is included in another model, and it can have different restrictions such as Read-only or Read-write permission applied to the model.

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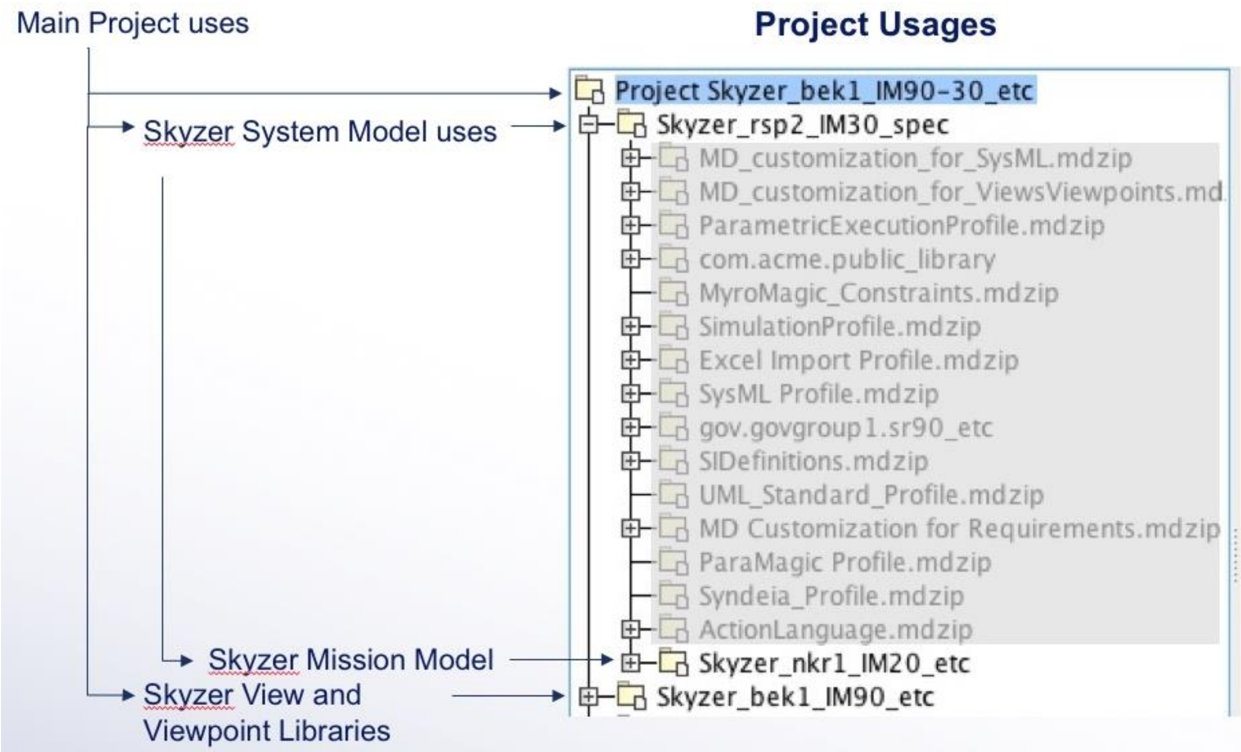

Figure 18. Project Usages for Skyzer Mission, System and Views[17]

The following enumerates a few use cases for Project Usages:

- Project Usages of Skyzer Mission Model in the Skyzer System Model to trace mission requirements to system requirements
  - Figure 18 shows that the Skyzer System Model has several Project Usages, such as the Project Usage of the Mission Model (IM20). This allows the System model to create traceability linkages from system information (e.g., behavior in state machine and activity diagrams) in the Skyzer System model (columns) to the Skyzer Mission requirements (rows) as shown in Figure 19. This requirements table is automatically generated. The rows of the table show the mission requirements that are visible inside the system model through project usage, and the columns show the system requirements.
  - This provides significantly more rationale through analysis for requirements. Some of the behaviors have simulations that allow reviewers to understand the broader implications through these dynamic views of a simulated model.
  - If Mission requirements are updated, this will be immediately visible in the System model, which may then need to be modified to address those changes in the mission model.
- Reuse Model Libraries of DocGen Viewpoints
  - We have collected and developed a number of Viewpoints (mechanism for extracting information from models to produce documents) in IM90 (Viewpoint Model). Our team is standardizing on Viewpoints, which adds uniformity to the

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generated specification. In addition, this means that very few modelers need to create or know how to create viewpoints.

    - The concept of views and viewpoints is widely used across the architectural community, having originated back in the 1970's where Ross's Structure Analysis and Design Technique used them, the concept of Views became widely accepted following the development of Kruchten's 4 + 1 architecture view model, they have since been formalized in the ISO/IEC/IEEE 42010:2011, Systems and software engineering — Architecture description (iasaglobal.org).
    - As part of the OpenMBEE, NASA/JPL developed an implementation for View and Viewpoints are part of the MDK/DocGen [64], which is extensively used to generate stakeholder-relevant views from all of the models used in the surrogate pilot
- Project Usages of Evaluation Model and Estimation Model
    - Our team is also working on an Evaluation Model to be used for Source Selection (see Section 2.6 for more details)

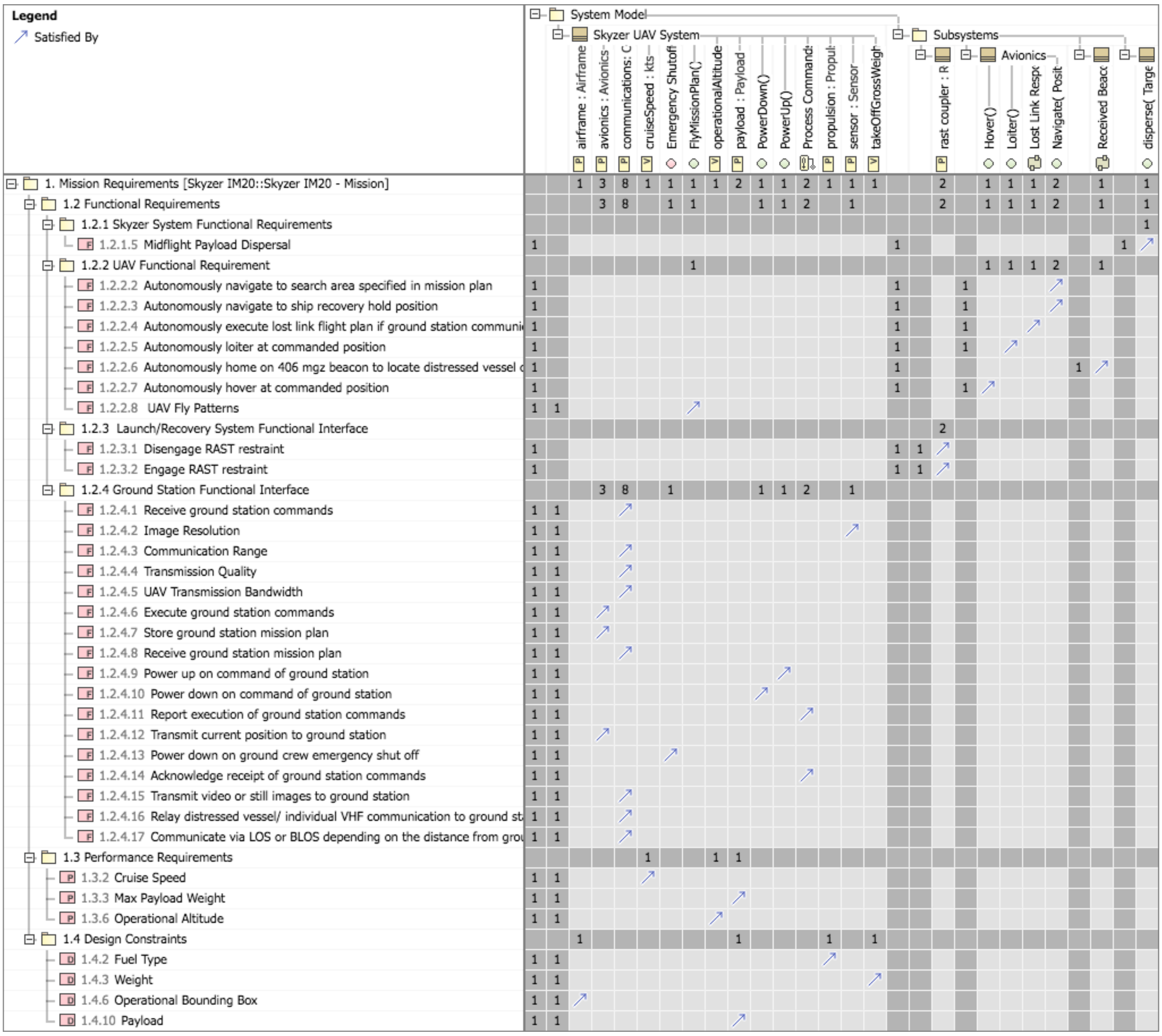

Figure 19. Requirements Traceability from Mission Requirements to System Requirements[18]

2.6 SOURCE SELECTION EVALUATION AND ESTIMATION MODELS

There is a video[19] that can be downloaded from the APAN Surrogate Pilot Group that captures both an explanation about the evaluation model and demonstration for how the Source Selection Evaluation and Estimation Models can be used by a government evaluation team to have a means for rationalizing some of the source selection responses. Briefly, this video describes:

- Approach to use an Evaluation model for the Key Performance Parameters/requirements in Source Selection Evaluation; this formalizes Section L, which is part of the SOW
- Approach to create an Estimation model for anticipating performance estimates to be provided in a Source Selection response

[18] NAVAIR Public Release 2019-443. Distribution Statement A – "Approved for public release; distribution is unlimited"

[19] Demonstration of Evaluation Model for Source Selection https://community.apan.org/wg/navair-set/set-surrogate-pilot/m/documents/241801

- Realization of important use cases for Project Usages mechanisms, for example:
  - We can separate almost anything we need, but combine them through Project Usages (e.g., IM30 System Model *Project Usages* IM20 Mission Model to trace system requirement and analyses to mission requirements). This way we know that if anything changes in Mission Model (IM20), System Model (IM30) will see that change and need to be updated appropriately.
  - How to use Project Usages to separate Estimation model from the Evaluation model. The Evaluation model can be provided to the contractor, so that we know it would work correctly when they provide their model at Source Selection. We do not give the Estimation model, but we (the government) uses both at Source Selection.
  - The Surrogate Contractor is using the Project Usages mechanism to include System Model (IM30), which again includes Mission Model (IM20).

The video discusses three different scenarios using the Skyzer System model to calculate margins for the required KPPs using SysML parametrics and equations. Two scenarios were discussed and demonstrated using an example in SysML:

- Evaluation Model: provides a template-based set of blocks to characterize the Evaluation Context for the system that can be looked at in terms of Minimum or Maximum Margin. The response to a performance requirement includes that specified by the government and that claimed in the proposal response/submission, which allows an equation to characterize the margin - if acceptable, then the response for the KPPs would be acceptable to the government
  - Demonstration showed where the Minimum and Maximum margin equations are defined in parametric blocks
  - How they are used in the Evaluation Context that maps the KPP of the System Model (linked to the Mission Model) to associated margins
  - One or more responses (submission from proposers) could be Project Usage into this Evaluation model used during Source Selection, where the simulations are run to generate the margins and tabularize the responses for comparison using Cameo Simulation Toolkit
  - The demonstration showed how the responses can be traced to the requirements and if the result is acceptable it could be labeled with the verify stereo type
- Estimation Model: the estimation model is similar in concept to the Evaluation Model, but would be developed so that a government evaluator has some type of "ball park" estimate for an expected value of each of the KPPs defined in the Evaluation Context; this model would not be given as part of the RFP.

As part of the Section L supplement to the SOW, an Evaluation Model was provided as GFI as part of the RFP to the surrogate contractor. The responders to the RFPs would be able to use Project Usages from their model to the Evaluation model in order run the evaluation constraints that are formalized as parametrics. As a caveat, there are limitations to what can be characterized in parametrics, and we need to provide other demonstrations as we continue through the Surrogate Pilot. An MDAO workflow that combines one or more solvers related to KPPs (e.g., endurance) could also provide a richer way to deal with more expressive computationally involved performance constraints as discussed in Section 4 .

2.7 REQUEST FOR PROPOSAL AND GOVERNMENT FURNISHED INFORMATION

The RFP included a government furnished model that had to interface with contractor models as part of the RFI response. In an actual program the government would need to provide a pre-RFP release step where the government would make available a practice version of the GFI model for the sole purpose of exercising the offerors model interfaces. All offerors would have the chance to exercise their interfaces to the "practice GFI" and send comments to the government if they have problems interfacing to the Evaluation Model. Based on comments received, the government would decide whether the GFI needed to be modified or the offeror would need to fix the interface of their interfacing model. Once the RFP was released, if any contractor could not get the model to work because they did not take advantage of the practice model, there would be no issue on the government.

An issue with this approach is that the GFI interfacing approach might not work with all of the commercial tools. We know that NAVAIR's first choice is the NoMagic tools, and the ASRM is being developed in Cameo System Modeler. While most companies use several different SysML modeling tools, not everyone may use NoMagic. There are possible work arounds including the use of OpenMBEE MMS as is discussed more in the context of our Interoperability and Integration Framework in Section 3.5.

2.8 LESSONS LEARNED SUMMARY

The following provides a non-exhaustive list of categorized observations and lessons learned topics from our Phase 1 efforts, with cross-reference links to other sections to explain some of the details and implications.

Category	Explanation/Examples
Identify objectives for each phase of the pilot (see Appendix A)	• We developed objectives using the NASA/JPL ontology in a model to capture high-level stakeholder-related concerns our questions about the SET Framework concept • Objectives were mapped into use cases that could cut across one or more objectives • We are tracing results (e.g., models, processes, observations) to illustrate examples associated with these objectives • We added new objectives as they were identified
Establish infrastructures for IME tools and AST as early as possible (see Section 2.4)	• This is a critical need, because one cannot exercise an MCE or MBSE project without sufficient tooling and methods • OpenMBEE and associated modeling tools provided key capabilities such as model management, DocGen, and View Editor (visualizing stakeholder-relevant views in a web browser) • Example AST provides understanding for AST versus Single Source of Truth • OpenMBEE is extensible to allow for research to integrate ontologies, semantic web technologies, and cross-domain linking of other models to demonstrate the art-of-the possible

	• OpenMBEE allowed surrogate contractor to have similar environment, which was useful for non-SysML subject matter experts to view, edit, and comment on models in View Editor; NOTE, editing in the View Editor must be performed on objects in order for the edits to be synchronized back to model, including MMS and Teamwork Cloud • Expertise is required for: 1) setting up OpenMBEE, 2) Teamwork Cloud (or SysML repository), 3) account management for OpenMBEE and Teamwork Cloud
Technically feasible to develop everything as a model	• While one may argue about the value of doing everything in a model, the pilot demonstrated that it is possible to develop everything in model (see Section 2.4 for the list of models), even for example the SOW • Key benefits of models: ▪ Focus on needed information and artifacts (not the form, form is embedded in model) ▪ Every model element can be check for uniqueness (there should only be one element for any type of instance, class, or relation) ▪ Every model element has its own unique identifier ▪ Every model element has its own history ▪ Establishing precise SOW language that should be more reusable in the future, and is moving away from a review-based perspective to focus on criteria about models reflecting maturing design
Establish model management practices early	• We identified the lack of model management in Phase 1 as an issue, but established better practices at end of Phase 1 and start of Phase 2 • We did model management with both OpenMBEE and the Teamwork Cloud, but need to develop better practices for branching analyses and then merging back into the trunk, which represents the AST • Model management is different from configuration management of software or documents • We asked NASA/JPL and other members of the OpenMBEE Collaboration group for documented practices, but found there are not many documented • We are using concepts of Gitflow for Phase 2 efforts; Gitflow Workflow is an established practice used for “agile” software development practices • Model management needs to factor tooling capabilities
Project Usages for Model Modularization (see Section 2.5)	• Project Usages is a capability provided in the NoMagic tools we are using in conjunction with OpenMBEE that provides a means for modularization of models in a manner analogous to concepts that has been around in software for including and reusing different software modules and libraries

	• Model modularization allows for links and reuse of many types of models, including mission, system, contractor, source selection evaluation • Modularization has potential for an approach to isolate classified information • Provides access controls at finer level of granularity • Helps modularize to reduce complexity
Create View and Viewpoints to provide stakeholder relevant views and leverage Viewpoint libraries	• View and Viewpoints provide the means for generating document-like views directly from model content, which provide stakeholder relevant information that can be viewed in web-browser or can produce a document in Word or PDF • Views provide a means for associating Digital Signoff with model views
Use Digital Signoffs as a means for evolving from CDRLs	• Digital signoffs have provided an example for how to transform CDLRs and DIDs in Authoritative Source of Truth • Digital signoff link criteria that is often required at different program review points to be linked to model evidence directly in the model • Digital signoffs are model objects that can be updated in the View Editor, but get pushed back into the model • Established a basis for metrics

Generated Views/Specs	• Standardize on DocGen Viewpoints to makes Views look consistent
	  ▪ We have/use a library of Viewpoints
	• Use SME Stakeholders to define relevant Views
	  ▪ Provides a means from transitioning from Doc-based to Model-based
	  ▪ Use standards to define the Views; for example, we used the Navy standard to define mission model View
	  ▪ Views provides a means to use an artifact-driven approach to enforce modeling methods
	  ▪ Program leadership will make an approval decision based on model generated stakeholder-relevant reports
	  ▪ Only modeler will likely know/understand what is in entire model; Views are tailored to specific stakeholder interests/concerns

Requirement management can be done directly in models	• Provides means for characterizing requirement directly with other structural and behavior analyses within the model • Leveraging Project Usage provides means for performing traceability from various related models (e.g., Mission, System, Contractor, etc.) directly in the models
Modeling provided a means to simplify SOW with emphasis in providing tool agnostic modeling information	• SOW and Evaluation Criteria focus strictly on the needed information • Focus on function of the information needed for source selection vs. form (e.g., in a Word Document)

	• Determine if SOW language characterizes minimal acceptable criteria for information that needs to be in the models or exposed model views, including for future baselines; this should probably be associated with Digital Signoffs or digitized criteria such as Section L
MDAO being applied by Surrogate Contractor	• Methods for ensuring that Government System Model is properly structured was required to use MBSEPak and ModelCenter; further demonstrates importance of model methods • MDAO provides a means to link Descriptive System Models and Discipline-specific Multi-physics models at the conceptual and parametric level
Establish and align modeling with methods & guidelines	• Defined modeling guidelines for the Surrogate Pilot SysML models for Phase 1, but being evolved for Phase 2 • Models for MDAO using ModelCenter and MBSEPak are necessary and were defined and documented • Methods for tagging KPP in mission models were developed • Methods for modularizations were developed using Project Usages • Mission modeling method based on Navy standard, but being evolved for Phase 2 • System modeling method based of OOSEM, but plans to align with NAVAIR Systems Engineering Method (NAVSEM) planned for Phase 2 • Phase 2 efforts are working to align models with Acquisition System Reference Model
Leverage social-media technologies for continuous communication to complement modeling in an AST	• APAN provided the means for journaling the events, results and lessons learned on a continuous basis and provided a means for sharing that information • This approach is effective for documenting weekly progress between team members, but it does take time to document and refine the meeting information • This journaling provides substantial input for these lessons learned • Original motivation was to share openly the objectives and results of the surrogate pilot experiments. Many people have joined the group, but the responses are low, and we are not sure if they are only watching and not open to commenting publicly on the Surrogate Pilot efforts • Videos from weekly meeting provide valuable information about evolving pilot, new techniques and approaches (e.g., Evaluation Model for Source Selection)
Surrogate Pilot demonstrated a new operational paradigm	• Communicating the proposed approach about a new operation paradigm for collaborative AST during the SET Industry resulted in positive responses from industry RFI responses

for collaboration in AST	▪ This can support continuous and asynchronous insight and oversight by the government ▪ This concept is planned after we simulate contract award for continuing Element 3 in Phase 1
Request for Information (RFI) as models useful to test new operational paradigm	• Do not provide mission model as GFI for RFI phase, because it may be too confusing to potential responders • Do use Views of mission model for appropriate context, such as those generated through DocGen for stakeholder-relevant views • Need some type of evaluation criteria for a model-based RFI response
Request for Proposal (RFP) as models is technically feasible	• Simulating Virtual Industry Days as part of pre-RFP process was useful to the pilot • Model (part of Section L) ▪ Can be distributed as GFI for Section L to ensure contractor model characterizes performance for KPPs
Technology enables collaborative capabilities in MCE	• Understanding Project Usage Use Cases for "including" models are important for many reasons: ▪ Skyzer System project uses Skyzer Mission to ensure traceability ▪ Skyzer RFP response project uses Skyzer System and Mission model ▪ Other use cases listed in Section 2.5 • Linking descriptive models with discipline-specific/domain-specific ▪ Examples emerging for integration of Descriptive Models are leveraging dynamic simulations from the SysML/UML level with one or more discipline-specific/domain-specific engines • Semantic approaches to tool interoperability gaining attention ▪ NAVAIR RT's have been emphasizing ontologies and semantic web technologies since 2014 ▪ Interoperability and integration demonstrated for RT-168 using semantic web technologies ▪ AGI discussed new technology for linking descriptive models with simulations elements across domains ▪ Navy Cross-SYSCOM ontologies ▪ Other companies: Intercax, NoMagic, AGI, Airbus using or adopting semantic web technologies • Use Glossary Capability in modeling clients to fully define terms
Issue tracking necessary	• Categorized issue tracking and notification was necessary especially when we neared the release of the RFP

	• Used native capabilities in OpenMBEE to allow use of web-based View Editor in order to eliminate need for more user ID and passwords on other tools
Releases should tag master branch as AST	• Agreed on using a stereotype (or Tag) for identifying Key Performance Parameters (KPP) • Release included model versions, but also tool versions used to produce the models

Competitive and Legal concerns for early collaboration using models	• Iterative interaction with surrogate contractor during RFI and pre-RFP very useful
	  ▪ Is there anything "illegal" with doing this
	  ▪ How would it work in a competition?
	• Need to address potential of unintentional data leak can enable a protest

Access to AST	• The AWS server is hosted in the public domain, and proved to be very effective for the non-government surrogate pilot team • There are restrictions on accessing the hosted models by the team members using government computers
Model exchange in AST	• Even though government and contractor teams used SysML with the same tool, specific methods need to be more explicitly characterized to support model exchanges, such as using the Source Selection Technical Evaluation Model and the use of proper methods to support use of MBSEPak for Model Center

High Performance Computing	• While storage is becoming inexpensive, the massive storage produces large amount of data, and there is a need for consideration for High Performance Computing (HPC), such as needed for:
	  • MDAO alternative analysis – we can generate hundreds or thousands of alternatives
	  • Use of reasoning such with ontologies, AI and Machine Learning

Workforce skills	• There is a likely need for new types of skills for government subject matter experts in order to navigate the digital information in environments such as, but not limited to:
	  • Views of models in a web browser
	  • Editing and commenting within a View
	  • Digital signoffs
	  • Navigating branches
	  • Model linking
	  • Issue tracking
	  • Navigating and reviewing with industry discipline-specific tools (e.g., Computer Aided Design, Computational Fluid Dynamics, Finite Element Analysis, Failure Models and Effects Analysis), including understanding modeling assumptions and model boundary conditions

Other	• Industry MBSE RFI suggested use of parametrics, which has been developed into an Evaluation and Estimation models (see Section 2.6) • Team SME with modelers ▪ SME may supply mission scenario and constraints in non-modeling representations ▪ Early mission requirements were provided to lead on mission modeling using a spreadsheet • Establish relationships with commercial tool vendors so that research is performed with advanced tools that are often used by industry

2.9 Roadmap Views

We particularly like the two-dimensional roadmap proposed by Airbus' Hartmann that was first shown at the NASA/JPL MBSE Symposium in 2017, as shown in Figure 30. We have adapted this concept from two perspectives; the first is a roadmap for technologies that are likely to enable DE, as shown in Figure 20. The second perspective is for a roadmap based on the DoD Digital Engineering Strategy goals reflected in the context of an evolution of Mission and Systems Engineering, as shown in Figure 21. A key reflection is that these roadmaps anticipate the increased need to formalize the underlying information model as we move to the right (i.e., future), which can exploit more computational automation such as (i.e., AI, machine learning, etc.), enabled by high performance computing.

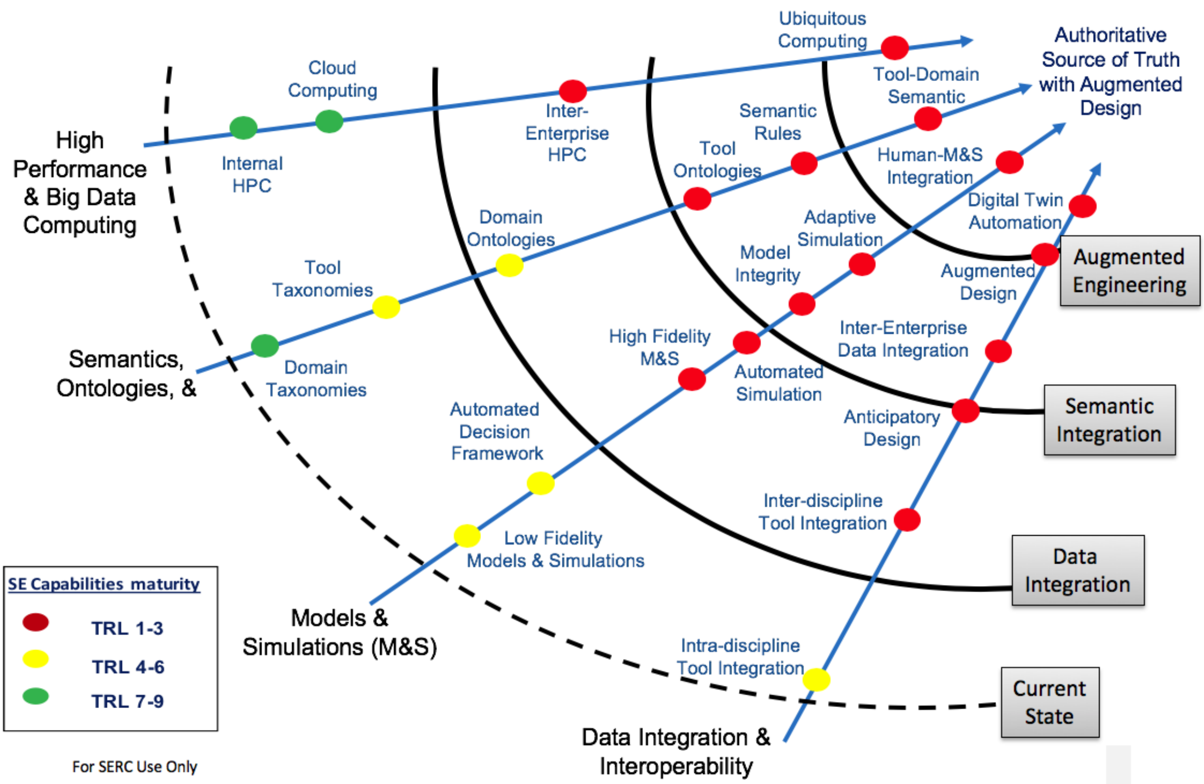

Figure 20. Roadmap for Enabling Technologies for Digital Engineering

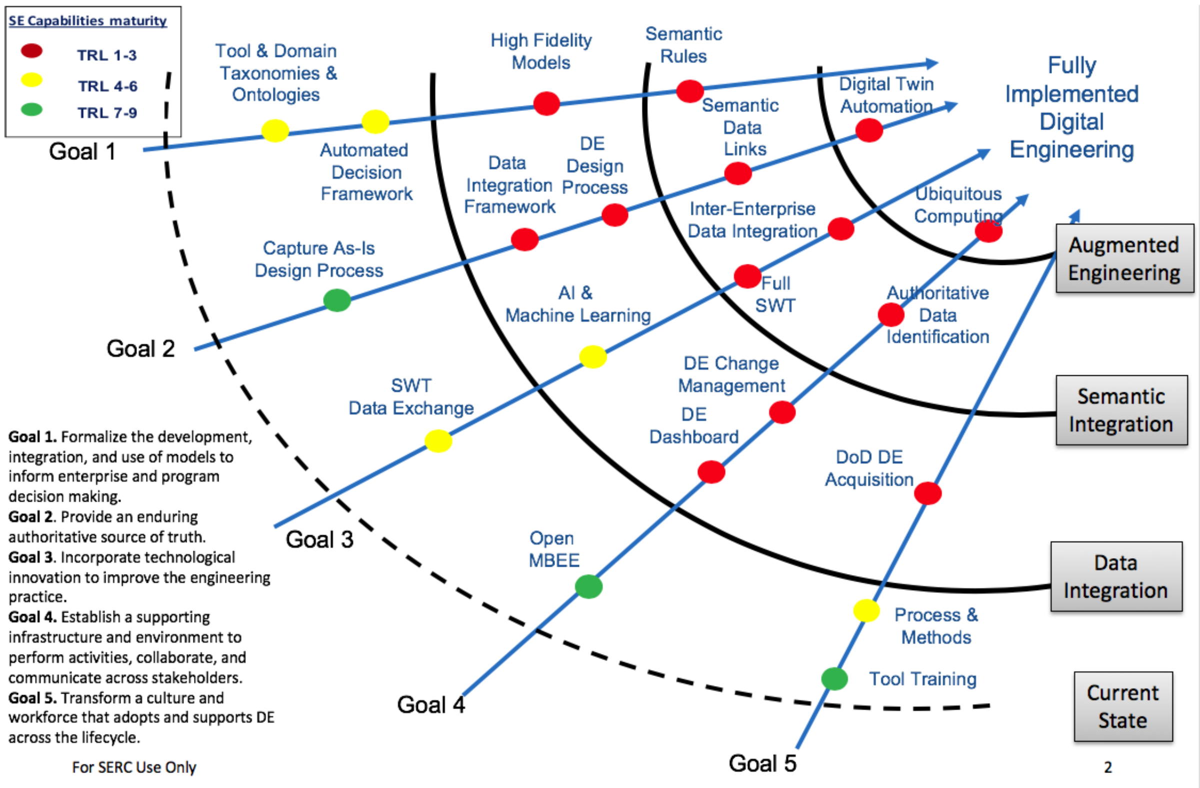

Figure 21. Roadmap in Context of Digital Engineering Strategy for Systems Engineering

2.10 Surrogate Pilot Next Steps

As reflected in Figure 6 the near-term focus is on:

- Phase 1 – Element 3
  - Collaboration Environment for performing reviews and assessing design maturing
    - Includes mechanisms to link discipline-specific design models to the descriptive models provided as GFI by the government, some of which have been demonstrated in the RFP response
  - Formalizing a Contract after Source Selection
  - Airworthiness for the deep dive elements of the Surrogate Contractor design
- Phase 2 – New Use Cases
  - Aligning Skyzer Modeling with ASRM and NAVSEM
  - Airworthiness to include broader aspects of airworthiness beyond the deep-dive for Phase 1 – Element 3
  - Model Management Guidelines to be used in Increment/Phase 2
  - Extend mission use case(s) to add at least one additional capability in order to address Capability Based Test & Evaluation (CBT&E) and Model-Based Testing Engineering, and attempt to apply the associated reference model for CBT&E
  - Formalization/synthesizing a "specification" from models for "RFP" and methods for providing models to contractor by characterizing the V&V criteria identified as a gap during Phase 1, and defining a means for incorporating the Digital Signoff criteria as part of the RFP; this requires new View and Viewpoints that align with ASRM
  - Transform CDRLs and DIDs and use Digital Signoffs in Authoritative Source of Truth

- Support assessment to determine how Digital Signoff related to Systems Engineering Technical Review (SETR) criterial can be subsumed or eliminated due to such capabilities as a collaborative AST
- Investigate approaches for creating Digital Signoffs in discipline-specific models

o Cyber security

- The only issue is that this will likely require software, and there has not been much software developed on the surrogate pilot

Additional use case candidates delayed from start of Phase 2 due to limited resources include:

- Scenarios for Alternative Analysis prior to "Milestone A"
- Mission Systems
- Logistics
- Dependability
- Creating a Project Management Model

2.11 Working Sessions and Sponsor-Supporting Events

A component of the research and required deliverables are conducting working sessions that inform the NAVAIR team about progress against the plan. These working sessions also inform the team about relevant information and feedback to scope the deliverables in the context appropriate for NAVAIR to leverage in SET; this has been especially important given the recent changes under SET. We also use bi-weekly drumbeats to share status and updates. Each working session has a defined agenda and the SERC research is always covered in the context of the surrogate pilot. The following provides a summary of the working sessions and other events, and a brief description of the contributions to the tasks and deliverables.

- Functional leads weekly meeting with SET leadership
- Conduct weekly meetings with the Surrogate Pilot team; meeting note and other relates resources are stored on All Partners Access Network (APAN).
- NAVAIR SE Transformation Working Session #39, February 22, 2018
- NAVAIR SE Transformation Working Session #40, April 19, 2018
- NAVAIR SE Transformation Working Session #41, May 17, 2018
- NAVAIR SE Transformation Working Session #42, June 21, 2018
- NAVAIR SE Transformation Working Session #43, August 9, 2018
- NAVAIR SE Transformation Working Session #44, September 27, 2018
- NAVAIR SE Transformation Working Session #45, November 15, 2018
- NAVAIR SE Transformation Working Session #46, March 14, 2019
- Participation in Bi-weekly Drumbeat

Other related NAVAIR/SERC events:

- NAVAIR Industry Day presentation on Systems Engineering Transformation Surrogate Pilot, March 8, 2018
- OpenMBEE Collaboration Meeting presentation on use of OpenMBEE for Surrogate Pilot, April 6, 2018
- Navy Tri-SYSCOM, Systems Engineering Transformation Surrogate Pilot, April 9, 2018
- SERC Advisory Board, SE Transformation via Digital Engineering, April 9, 2018

- Phoenix Integration webinar (Invitation): Applications for Three Research Use Cases in Model Centric Engineering using ModelCenter and MBSEPak, International Users Conference, April 17, 2018
- ARDEC Working Session #8, Share updates on Surrogate Pilot, February 21, 2018
- ARDEC Working Session #9, Share updates on Surrogate Pilot, April 3, 2018
- ARDEC Working Session #10, Share updates on Surrogate Pilot, May 31, 2018
- SERC Research Colloquium, July 12, 2018
- ARDEC Working Session #11, July 31, 2018
- Navy and DoD Ontology Workshop, September 18-19, 2018
- National Defense Industry Association (NDIA) Systems Engineering Conference, October 22-25, 2018, with presentation title:
  - Systems Engineering Transformation Surrogate Pilot Use Cases Enabling a New Operational Paradigm for Acquisition
  - Semantic Web Technology Architecture to enable Digital Thread
  - Collaboration in an Authoritative Source of Truth Environment using OpenMBEE
- Presentation on Surrogate Pilot and Lessons Learned for Functional Area Leads on September 26, 2018
- SERC Sponsor Review, presented Surrogate Pilot status and overarching SE Transformation objectives, November 8, 2018
- SERC Advisory Board Meeting, presented Surrogate Pilot status and overarching SE Transformation objectives, December 18, 2018
- NAVAIR Cross SYSCOM SE Transformation Technical Interchange Meeting #3, January 15-16, 2019
- NASA JPL MBSE Symposium, January 23-25, 2019
- INCOSE International Workshop with MBX Ecosystem meetings to present SERC Research, January 26-29, 2019
- ARDEC Working Session #13, Share updates on Surrogate Pilot, February 7, 2019
- Conference on Systems Engineering Research presented Surrogate Pilot approach to Authoritative Source of Truth, April 4, 2019
- SERC Model Centric Engineering Workshop on Enablers for Systems Security and AI-based Solutions – A Colloquium, April 16-17, 2019
- Weekly participation on research related to System Engineering ontologies in the Semantic Technology for Systems Engineering (ST4SE); Dinesh Verma initiated an effort with the support of Chi Lin, Steve Jenkins and Mark Blackburn to bring a community of people together in an attempt to create and ecosystem on Semantic Web Technologies
  - Started with a meeting that was held at NASA JPL on March 22nd on the subject
  - Core ST4SE team general meets bi-weekly and there have been three face-to-face meetings
- Bi-weekly participation in the Open Collaboration Group for MBSE that is providing support for adopting and contributing to OpenMBEE
  - This was critical to our success in deploying OpenMBEE for the Surrogate Pilot
  - Mark Blackburn is part of the OpenMBEE leadership team
  - Benjamin Kruse is part of the OpenMBEE committers team
- Weekly Surrogate Pilot team meetings (many recorded) with updates and status
  - Current team is approximately 32, including six (6) from SERC, and the rest from NAVAIR or NAVAIR contractors

    - Details provide at APAN.org @ https://community.apan.org/wg/navair-set/set-surrogate-pilot/; group has 190 members

2.12 Coordinated Acquisition Systems Reference Model Review

We coordinated getting leaders from industry to support the NAVAIR Acquisition System Reference Models review. As part of the NAVAIR SE Transformation effort, a suite of ASRMs are under development. There are multiple objectives for the ASRM that include, but are not limited to:

- Provide guidance and direction for new and existing models
- Used as a testbed for new processes, procedures, and analyses
- Initial ASRM, will establish high-level requirements for two examples: 1) Rotary Wing, and 2) Initial Carrier based UAV models

The ASRM is early in the development process, however NAVAIR wanted leaders from Industry to provide a peer review that was open to discussing almost all facets of the model, approach and additional considerations. This provides industry with the opportunity to make constructive comments on representation and content that will likely be provided as "System Model(s)" as GFI as part of future solicitations such as RFI or RFPs.

NAVAIR conducted two events:

1. Kickoff Meeting, July 11, 2018
    - Agenda
        - Briefing of the goals, approach, objectives, model overview, and expected outcomes of
        - Details of the review planned for August 8, 2018
        - Delivery of the briefing to be provided in advance
        - Delivery of the model
        - Distribution notice
2. Review Meeting, August 8, 2018
    - Face-to-face meeting with the reviewers, but virtual connection was provided
    - Agenda to be finalized, but tentatively will cover:
        - Welcome and Introductions (15 minutes)
        - Short review of the SE Transformation to put ASRM in context (15 minutes)
        - Update on approach, objectives, and expected outputs provided at Kickoff (30 minutes)
        - Model Overview and explanation of updates since the July 11th delivery (60 minutes)
        - Open forum for comments, questions, and critiques (~90 minutes)
        - Plan for the future, actions and closing

While the intention is to have significant feedback in a forum that has representations from NAVAIR and industry stakeholders, NAVAIR recognizes that reviewers may need more time to provide feedback, and therefore we would anticipate some form of written feedback or meeting within approximately one month from the review meeting in order for the ASRM team to move towards completion of the first baseline of the ASRM.

2.13 Coordinated Navy Ontology Workshop

In April 2018, NAVAIR, NAVSEA and SPAWAR, the three Navy systems commands decided to initiate a major SET initiative to create a plan to build a Navy SYSCOM and DoD Ontology to support this initiative. However, they also want to leverage other services across the DoD and leverage synergies from other related ontology developments (e.g., Joint Doctine). We helped our NAVAIR coordinate a workings session to be held in Washington DC on September 18-19 with representatives from the Navy SET team attending together with a number of persons with expertise in ontology as applied in the military domain.

As part of the Navy SYSCOMs SET we plan to create a suite of modular ontologies covering Naval domains using a hub-and strokes architecture with Basic Formal Ontology (BFO) as upper ontology. These modules will leverage existing resources wherever possible. The ontologies are designed to serve as an enabler for model-based systems engineering (MBSE), to promote interoperability of data and information systems, and to create common terminology across domains.

The goals of the September meeting are to review a draft version of the plan that will be distributed in advance to all participants in the meeting, and to identify existing relevant initiatives and potential collaborating partners across DoD and beyond. We want to bring subject matter experts that have knowledge of the integrated dictionaries and lexica that are the authoritative sources of the terms used across the Navy domains. These provide the basis for defining the classes for a modular set of ontologies. Day 1 was designed to be of general interest to both Navy and external participants. Day 2 focused on more specific issues of interest to the Navy participants.

Organizing Group:

- Dr. Barry Smith – Lead
- Dr. Mark Blackburn – Support for Lead
- Mr. David Meiser – NAVAIR Lead
- Dr. Dinesh Verma

2.14 Deliverables

As required by the contract, we produced:

- Technical Management and Work Plan
- Interim Technical Report
- Bi-monthly status reports
- Final Technical Report

We have also produced models, demonstrations, videos, examples and assembled tools for an IME for the surrogate pilot. The following provides a list of models that have been produced and supplied to NAVAIR:

- APAN (apan.org)
  - Tracking progress of the surrogate pilot using Discussion group that is linked to related evolving artifacts

  - Posting documents into both the general NAVAIR SET area as well as the Research area
- Successfully created instantiation of OpenMBEE both at Stevens and on (AWS) to be used in the surrogate pilot
- Demonstration of OpenMBEE Model Development Kit (MDK)/DocGen
- Automated OpenMBEE installation mechanism using Docker [70]
- Surrogate Project Plan Model
- Surrogate Mission Model for Skyzer
- Surrogate System Model for Skyzer
- Skyzer Request for Information package
- Skyzer Statement of Work Model, and associated Section L & M (Technical Evaluation Criteria)
- Skyzer Request for Proposal (RFP) Response by Surrogate Contractor
  - Source Selection Technical Evaluation embedded in RFP Response Model
  - Measures and Metrics Derived from Models, December 14, 2018, leads to measures/metrics
    - How many Digital Signoffs are in the model
    - How many Digital Signoffs are approved, rejected, undefined (no action taken)
    - How many Digital Signoffs have a risk higher than Medium
    - Rate of Approval Signoffs
    - Ratio of Rejected Signoffs (to total)
    - See Video: https://community.apan.org/wg/navair-set/set-surrogate-pilot/m/documents/253172
- Use cases, demonstration and video for doing Digital Signoff in the model (View Editor) against example criteria from the System Requirement Review (SRR)
- Briefing on creating SysML Activity Diagram for Monterey Phoenix in support of RT-176
- MDAO demonstrations
- Videos for the operations of OpenMBEE with Teamwork Cloud to be used on surrogate pilot
- RFP Configuration Index for Surrogate Pilot Release:
  - For the RFP (Request For Proposal) there are read-only tags created in the View Editor, capturing the state of the documents.
    - There are RFP tags for Mission Model Views IM90-30, System Model with Views IM90-20, IM20, IM30 spec, IM30 evaluation and SOW.
    - Their documents can be downloaded as pdfs here: https://community.apan.org/wg/navair-set/set-surrogate-pilot/m/documents/235974
    - The matching SysML models are available here: https://community.apan.org/wg/navair-set/set-surrogate-pilot/m/documents/235977
  - Their project versions in Teamwork Cloud are:
    - IM90-20 mission model with views: v.29
    - IM90-30 system model with views: v.35
    - IM30 system model: v.39
    - IM30 evaluation model: v.35

- IM20 mission model: v.15

- The used tools and their versions are:
  - Magicdraw 18.5 SP3 or Cameo Systems Modeler 18.5 SP3
  - MDK plugin v. 3.3.6
  - MMS v. 3.2.2
  - View Editor v. 3.2.1
  - Teamwork Cloud 18.5 SP3

Part II: Task Detail Summary

Part II provides details associated with the research use cases listed in Section 1.1. An extensive amount of material covered in Part II of the RT-141 final report [25] and RT-157 final reports [26] is still relevant information to this research, but has not been included in this report. For the convenience of the readers, we include some of the key topics from those reports:

- Traceability and scope of data collection of state-of-the-art MCE relevant topics collected from global scan of industry, government and academic
- Characterization of canonical reference architecture of an Integrated MCE Environment, some of which are represented in the AST shown in Figure 10
- Model cross-domain integration within the underlying single source of truth
  - Information Model for an Authoritative Source of Truth
  - Requirement ontology
- Model Integrity – developing and accessing trust in model and simulation predictions
- Modeling methodologies
- Multidisciplinary Design, Analysis and Optimization (MDAO)
- Example models
- Modeling and Methods for Uncertainty Quantification
  - Dakota Sensitivity Analysis and Uncertainty Quantification (UQ)
  - Overview of Quantification of Margins and Uncertainty
- Modeling Methods for Risk

3 UC00: Ontologies and Semantic Web Technologies

This use case investigates the development and use of ontologies and more generally semantic web technologies (SWT) for reasoning about completeness and consistency across cross-domain models. These capabilities support enforcement of modeling methods and support for model integration through interoperability. We summarize some research efforts and findings related to SWT in this section. For example, we have developed the Interoperability and Integration Framework (IoIF) under RT-168 [28], which has been used for preliminary demonstrations to support this concept using a domain and model agnostic decision ontology.

There is increased interest in the topic of ontologies and SWT as awareness has increased significantly in the past two years. We believe SWT may be enablers for an AST, approaches to methodology enforcement, and conformance that also support model integrity as reflected in Figure 7. Barry Smith who led the team that developed the Open Biomedical Ontologies (OBO) has joined our team. Barry also led the development of the Basic Formal Ontology [169]. OBO contributed to solving the human genome, but also exemplified how to develop modular and interoperable ontologies using BFO. As we discussed in Section 2.13, we are coordinating a working session to develop a plan for creating interoperable Navy and DoD domain ontologies in September 2018. Barry will lead the effort to develop the plan for creating the Navy SYSCOM and DoD ontology.

This section summarizes some of the relevant efforts researched over the past year on this topic in addition to the description and examples that explains how we are using the NASA/JPL IMCE ontologies [121] in the surrogate pilot (See Appendix A). It is also important to note that SWT is an enabler for capabilities such as Artificial/Augmented Intelligence (AI) and Machine Learning, because they provide a means for representing knowledge. We see these capabilities coming to use in both the systems we build and deploy, as well as in the systems engineering systems we use to analyze and development systems moving forward.

As described in earlier technical report such as RT-170, some organizations, like Airbus reported at the NASA/JPL MBSE Symposium in January 2019 on their evolving using of ontologies and semantic web technologies as part of their integration and interoperability strategy. There are a number of recent efforts that we have been made aware of that are starting to use ontologies with the concept of interoperability as a means for integrating descriptive models with other types of models (Haun, G., OpenMBEE Collaboration Group talk, Sept 4, 2018 – not yet published). The SysML version 2.0 is looking to formal semantics for the metamodel.

3.1 CHALLENGE OF CROSS-DOMAIN MODEL INTEGRATION

We believe that organizations should take advantage of tool-to-tool integration when possible, but in working with our sponsors and interacting with industry and government organizations, this is not always possible or it can be challenging. The challenge of cross-domain modeling integration can be illustrated using the following example. While an aircraft may have thousands of objects, consider the relationships for a refueling value of a UAV, as shown in Figure 22. There is one object discussed in this example (i.e., Valve), however, there are many domains that bring in cross-domain relationships to that Value, along with other objects, such as:

- Mechanical **Domain**
  - Valve connects to a Pipe
- Electrical **Domain**
  - Switch opens/closes Value
  - Maybe using combinations of hardware and software
- Operator **Domain**
  - Pilot remotely sends message to control Value
- Communication **Domain**
  - Messages sent through networks: 1) within the aircraft system, and 2) from the remote operator
- Fire control **Domain**
  - Independent detection to shut off Valve
- Safety **Domain**
  - Looks top-down at potential hazards through Fault Tree Analysis (FTA)
  - Looks bottom-up using Failure Models and Effects Analysis (FMEA) to analyze failure impacts from specific designs of components

Figure 22. Example of Cross Domain Relationships Needed for System Trades, Analysis and Design

A problem is understanding the cross-domain impacts of designs and analyses that might be needed if one object within these related domains change. In general, there are different tools used in different domains, and the tools are often not integrated, nor are they able to share semantically-relevant data. Tool integrations are often dynamic consequences of customer requirements to continue improving the tools, thus the tools are constantly being updated, which further adds to the challenge of tool-to-tool integration. Tool integrations are not simply statically putting a certain set of tools together. Depending on the varying needs of tasks from particular stakeholders, the types of tools needed, their execution sequences, the interdependencies of data flow among them vary from case to case. In addition, the problem often gets worse when attempting to maintain an integration for different versions of tools. Figure 23 illustrates the dynamic nature of tool integration [162].

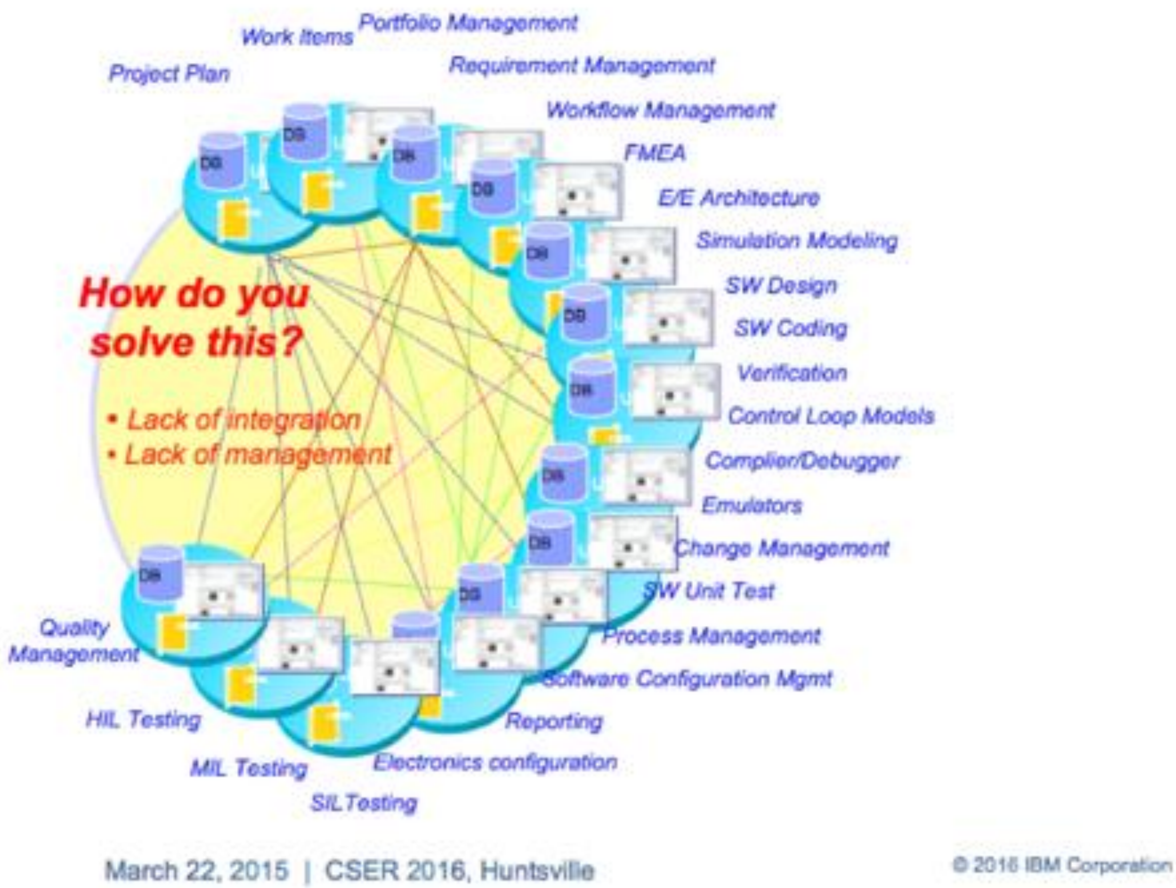

Figure 23. Coordination Across Tools Based on User Story

As shown in Figure 24 [58], there can be a very large set of tools that can be used to support analysis and develop the needed data and information across all of the domains. Notionally the Reference Technology Platform (RTP) [7] is the collective set of tools that an organization has in their inventory. Any specific program creates a RTP instance. A key challenge is integrating the assembled tools, especially when they may not have been created to be integrated, and equally important is that the methods for assembling and using these analysis workflows is largely in the heads of a few subject matter experts, as explained by our sponsors. Therefore, it is important that appropriate methods are applied to the selected tools that are assembled for use on a project or program. As a secondary objective that is being demonstrated as a leading-edge approach by NASA/JPL is to ensure models are created that comply with established modeling patterns that have been formalized using ontologies. We provided information on the NASA/JPL approach, which transforms the model information into a tool-neutral AST based on ontologies, and then uses standard SWT to apply checks to ensure completeness and consistency [101].

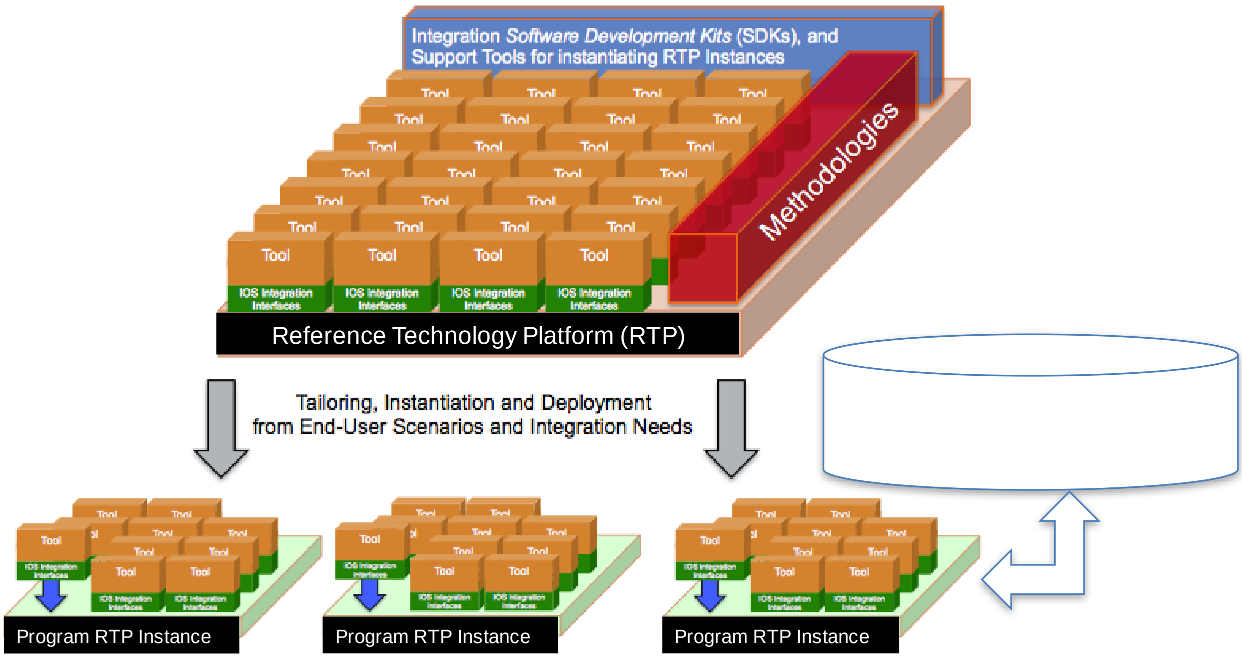

Figure 24. Appropriate Methods Needed Across Domains

3.2 SEMANTIC WEB TECHNOLOGIES AND ONTOLOGIES

Briefly, the SWTs are based on a standard suite of languages, models, and tools that are suited to knowledge representation. Figure 25 provides a perspective on the SWT stack, which includes eXtended Markup Language (XML) [134], Resource Description Framework (RDF) [188], Web Ontology Language (OWL) [185] (i.e., OWL2), the SPARQL Protocol And RDF Query Language (SPARQL) [189], and others. RDF can describe instances of ontologies – that is, the data for particular model instances, where OWL relates more to metamodels describing the class of information and relationships that can be characterized as RDF instances. The SWT was created to extend the current Internet allowing combinations of metadata, structure, and various technologies enabling machines to derive meaning from information, both assisting and reducing human intervention. This technology is generally applicable to many different applications, and we discuss a few in the following section.

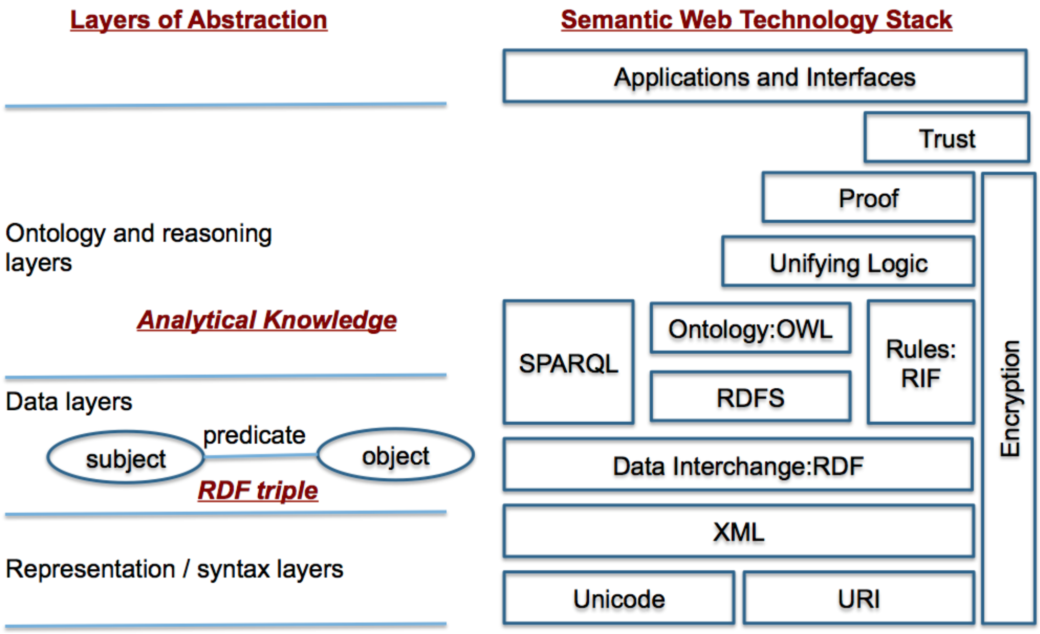

Figure 25. Semantic Web Technologies related to Layers of Abstraction

3.3 NASA/JPL Integrated Model Centric Engineering (IMCE) Ontology

Our research is beginning to reflect through demonstrations and presentations some of the different uses of SWT and ontologies. The following figures have been taking from *Model-Centric Engineering, Part 3: Foundational Concepts for Building System Models*. Figure 27 shows the IMCE ontology concept that is being evolved by NASA/JPL. Their process involves:

- Creating the foundational IMCE systems engineering ontologies [121] derived from modeling patterns (reflected in Figure 26), including:
  - Mission ontologies
  - Project ontologies
  - Analysis ontologies
  - The rationale underlying these ontologies are currently being documented by NASA/JPL's Steve Jenkins are part of a new effort called the Semantic Technologies for Systems Engineering Foundation
- The ontologies can be created with any OWL modeling tool such as the open source Protégé
- The ontologies are transformed into SysML profiles
- The SysML profiles are loaded into a modeling tool (MagicDraw in this case) for creating models
- The profiled SysML models are exported back into OWL statements
- Checks for completeness, consistency and well-formedness can be performed

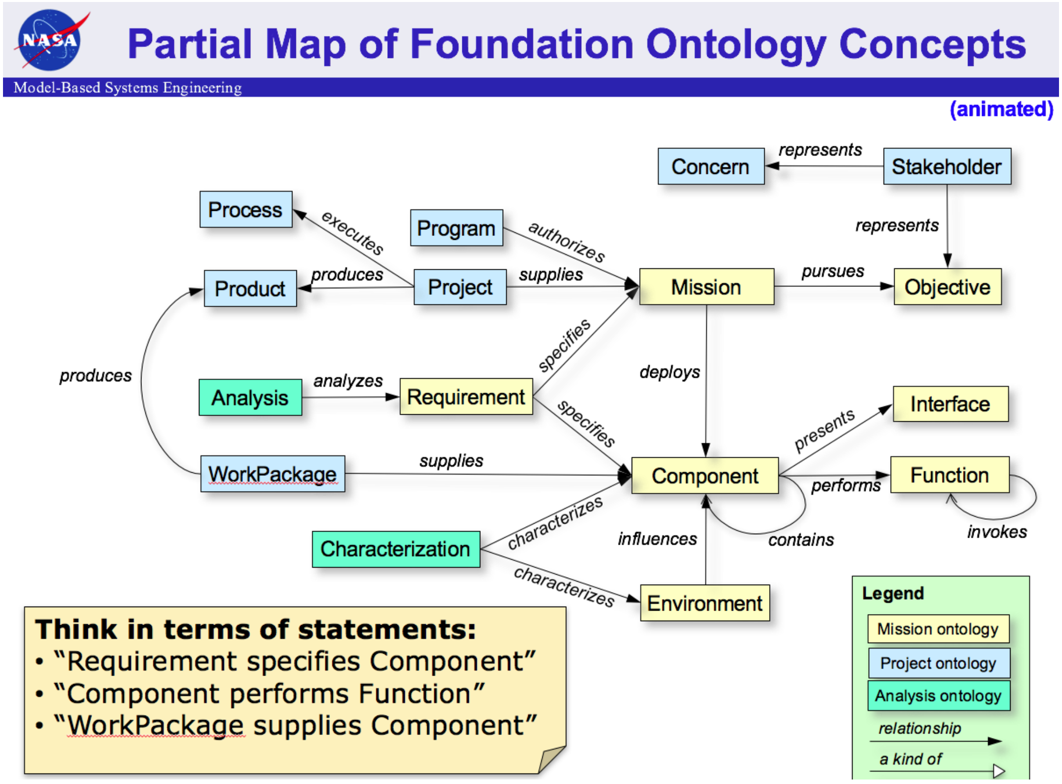

Figure 26. NASA/JPL Foundational Ontology for Systems Engineering

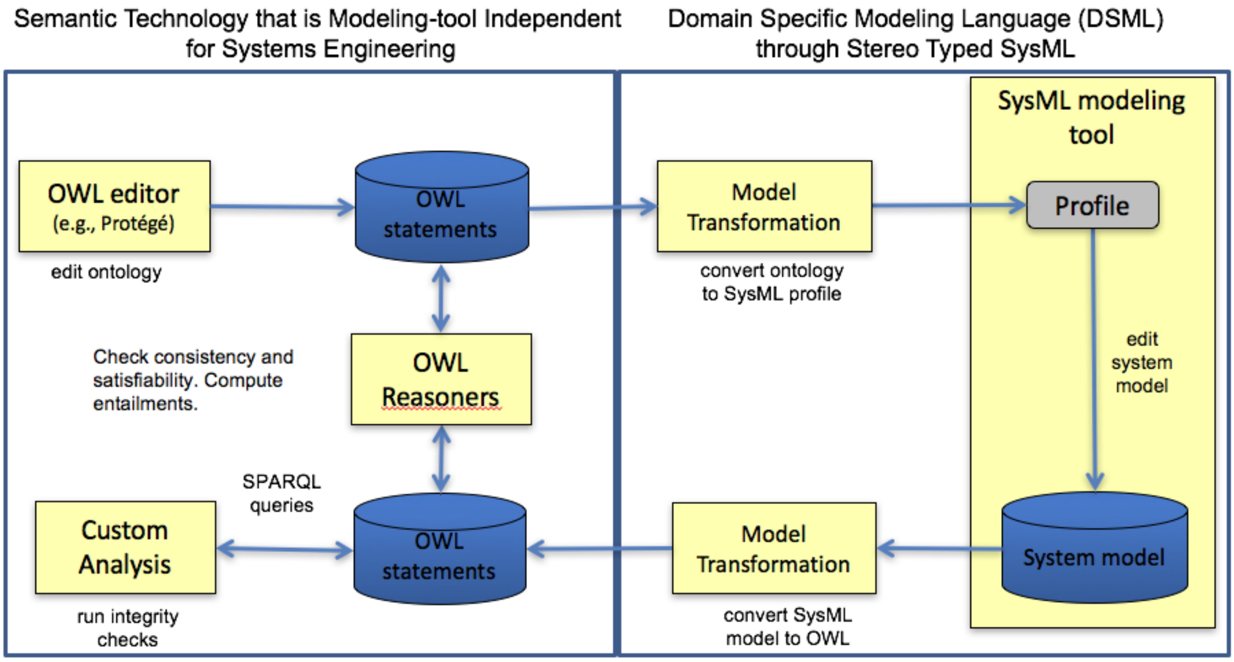

Figure 27. From Ontologies to SysML Profiles and Back to Analyzable OWL / RDF

Figure 28 shows the various representations associated with the concept described in Figure 27:

1. The modeled statement in English is: "Component performs Function"
2. The OWL/RDF representation of the statement in low-level XML for this same statement
3. The Profile and Stereotypes used in the model (loaded into a SysML model)

4. The Stereotypes used in a SysML Block Definition Diagram (BDD) – while SysML is the graphical language that is used, the stereotypes derived from the ontologies effectively make the use in SysML into a Domain-specific Modeling Language

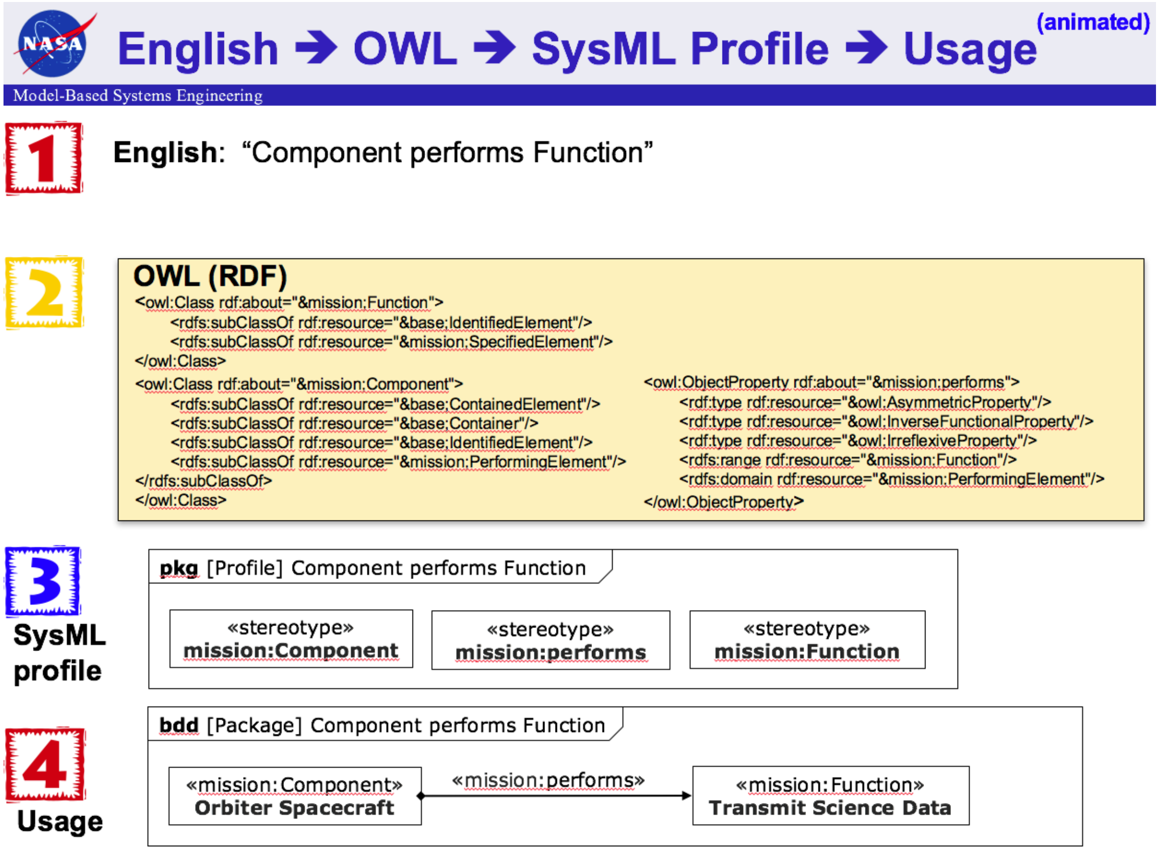

Figure 28. Multiple Representations in Process

3.4 Digital Environnent at Airbus Space

We have discussed the importance of an underlying information model (e.g., ontology) to enable the cross-domain integration of information in an AST [25]. The concept of semantic analysis that is integrated within the Integrated Modeling Environment (IME) is not limited to NASA/JPL. Ralf Hartmann, the Vice President of Enterprise Digitization for Airbus, gave a presentation at the NASA/JPL Symposium and Workshop in Jan 2017 [87], continued the message at the Phoenix Integration International Users' Conference in April 2018 [88], and had three related presentations at the NASA/JPL Symposium and Workshop in Jan 2019. While there were many points made in these presentations, of particular interest was a historical perspective on how they have been assembling a system design engineering environment to cover the entire lifecycle. The representation of the environment as shown in Figure 29 was particularly interesting as it relates to the concept of a semantically rich information; this pertains to the box in the middle call RangeDB Data Management. This replaced a commercial product with their own infrastructure functionality (i.e., "secret sauce") that provides a Semantic Data Model for multi-disciplinary Integration as shown in Figure 31. This effort confirms why we believe SWT will play a key role to characterize the underlying information model for both ARDEC and NAVAIR, and again reflects positively on the NASA/JPL use of SWT as discussed in this section.

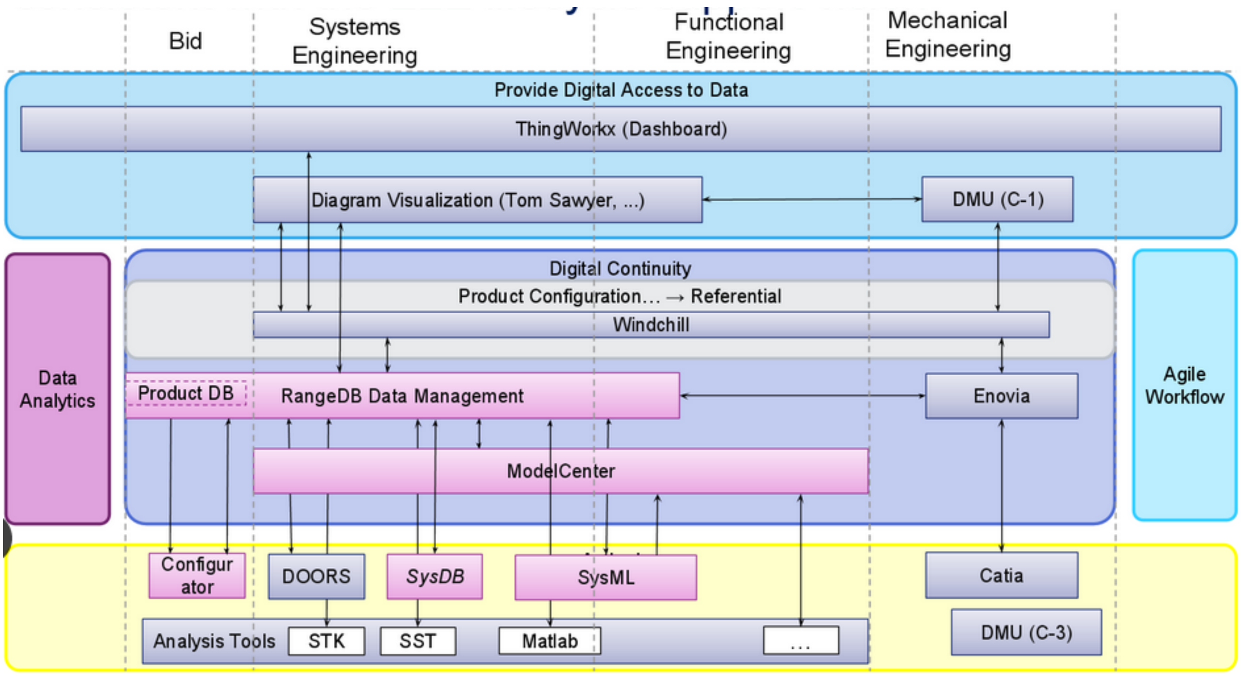

Figure 29. Airbus Digital End-to-End (System & Product) Engineering

Finally, the Hartmann briefing also included an associated roadmap as shown in Figure 30 that was structured in two dimensions:

- Technology clusters
  - Requirement engineering & V&V
  - MBSE and design
  - Engineering data lifecycle management
  - Collaborative engineering
- System engineering technology integration levels
  - Data integration (just connecting data)
  - Semantic integration (identifies rules how to connect and understand data)
  - End-to-end (knowledge management)

The key reflection on this roadmap is acknowledging the increased need to formalize the underlying information model as we move to the right (i.e., future), which can exploit more computational automation such as computational intelligence (i.e., AI, machine learning, etc.), enabled by high performance computing.

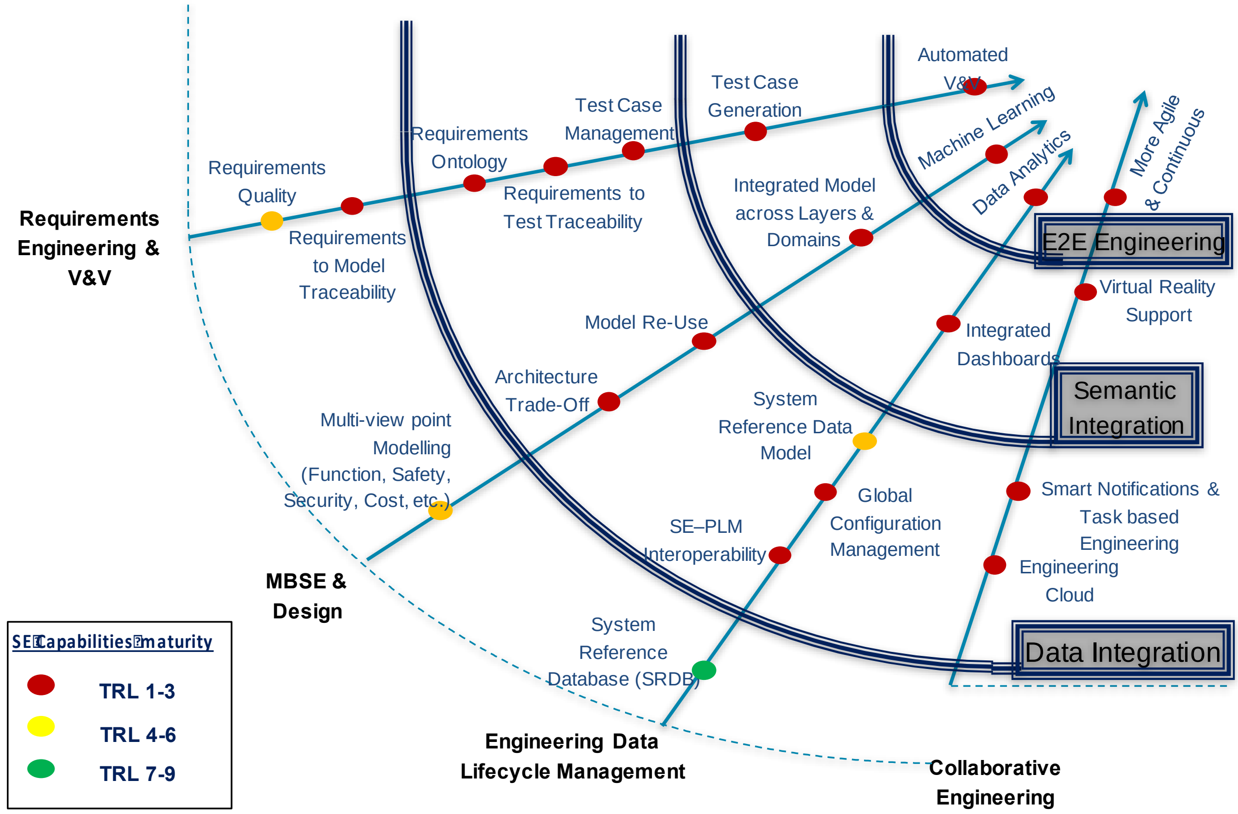

Figure 30. Airbus Roadmap Shown Bands of Digital Engineering Integration

3.5 Integration and Interoperability Framework (IoIF) with Semantic Web Technologies

The SERC RT-168 research team continues to evolve the IoIF and integrate other capabilities with emphasis of demonstrating interoperability through SWT [28], as shown in Figure 31. We demonstrated a Decision Framework enabled by SWT with a decision ontology starting from a system model in SysML. This system model represents a number of UAV alternatives derived from a book chapter developed by Matt Cilli [51]. We demonstrated tool-to-tool integrations, for example the UAV SysML model integrates with ModelCenter, through MBSEPak, to illustrate the MDAO concept for alternative analysis (see Section 4.6). The demonstration uses OpenMBEE MDK plugin to transfer SysML information to MMS. IoIF capabilities transform the SysML information stored in OpenMBEE MMS into the IoIF SWT (i.e., RDF4J triple store) to align with the decision ontology. The transformed information from MMS, now stored in IoIF SWT is transformed into a representation to support visualizations of the various tradeoffs in Tableau [174]. IoIF now provides a substantial foundation for follow-on research and other synergies that have been discussed with our sponsor about elevating the Decision Framework concept in the context of IoIF to mission scenarios, or combinations of mission scenarios given system capabilities that can be composed into mission capabilities.

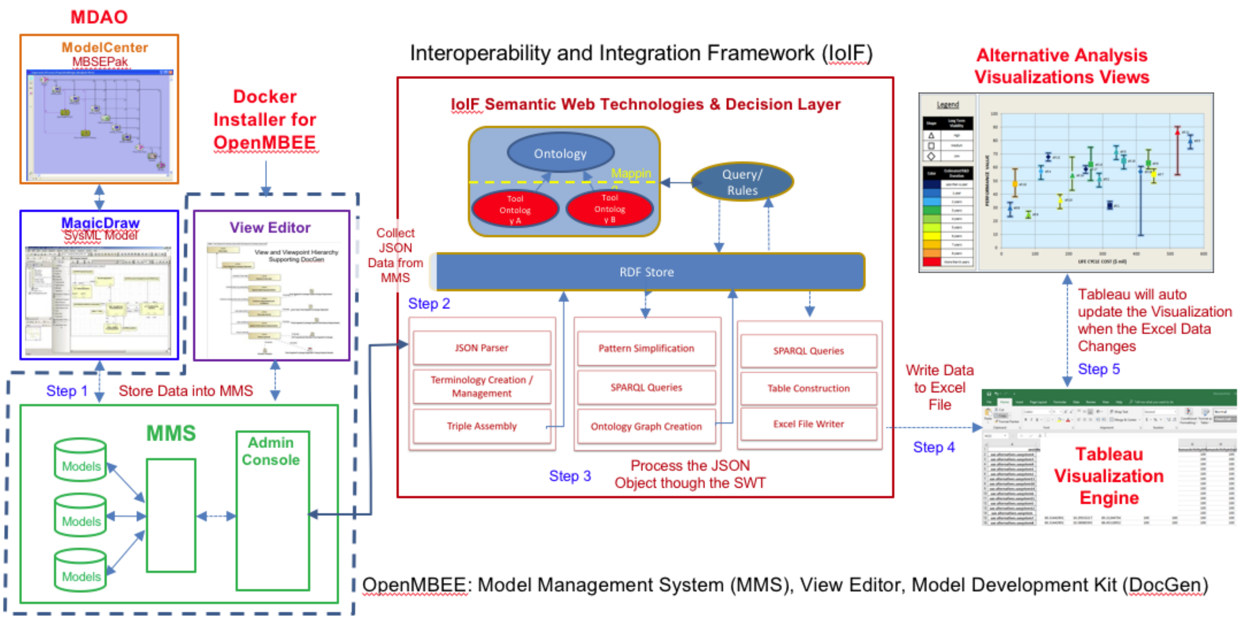

Figure 31. Interoperability and Integration Framework (IoIF)

3.6 Decision Framework Related to Cross-Domain Integration

Working with our ARDEC sponsors and collaborators, we have advanced the concept of the Decision Framework and demonstrated the technical feasibility of capturing needed input information from models as discussed in Section 3.5. Figure 32 provides a perspective on tradition systems engineering flow to illustrate where the Decision Framework fits into the overarching analysis workflow:

- CONOPS derived from simulation and gaming technologies are used to look at scenarios for trade space analysis of mission alternative
- "What" we want – requirements and constraints for a system of System of Systems (SoS) mapping back to the mission requirements
- "How" (1 or more) – designs to achieve the "What"
- "How well" (usually many) to assess the "How" using analysis, testing, reviews and assessing how the design satisfies the requirements, given the constraints to achieve the mission concept
- The underlying Information Model (ontology) links the data or metadata from many different domains
- We have demonstrated the initial viability of this Decision Framework concept as implemented through IoIF as shown in Figure 31

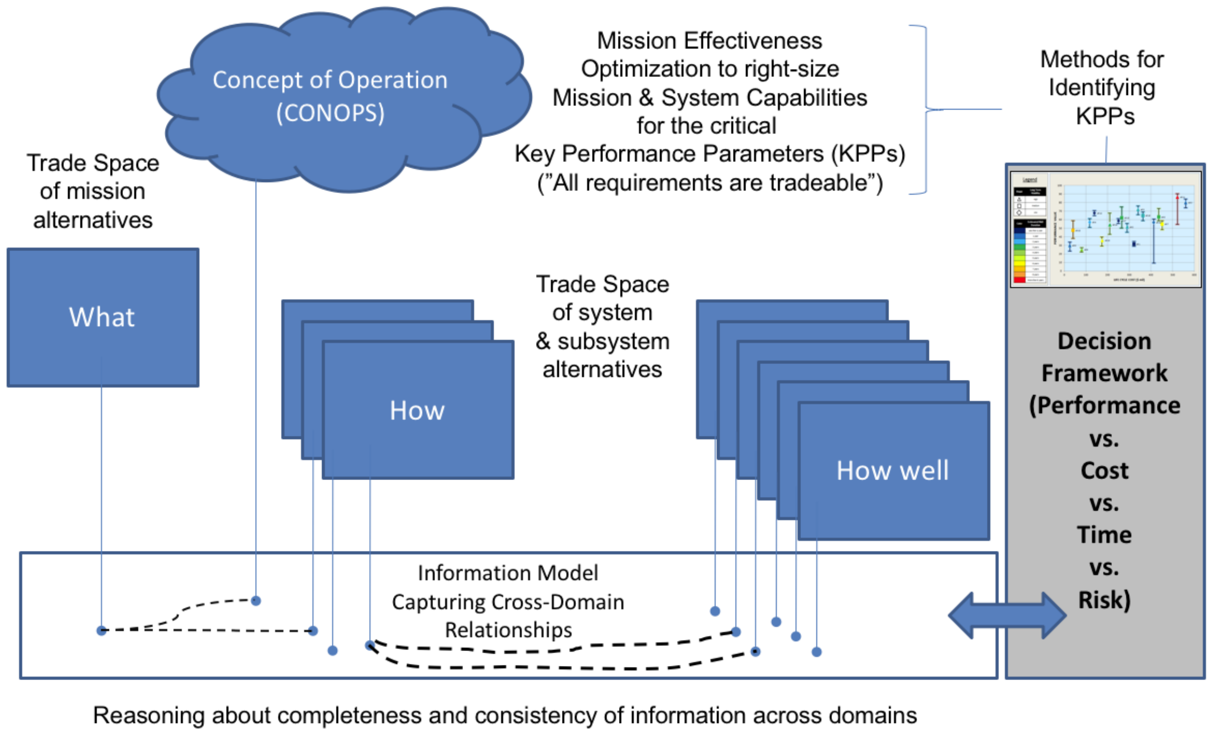

Figure 32. Context of System Engineering of Challenge Areas

As discussed in the next use case, we have developed using Phoenix Integration's ModelCenter [146] and MBSEPak, with SysML a way to formalize some of the inputs needed for the Decision Framework.

4 UC01: Multidisciplinary Design, Analysis and Optimization (MDAO)

This use case discusses various uses of Multidisciplinary Design, Analysis and Optimization (MDAO) at the mission, system and subsystem levels, which provides a means for continuous assessment of trades (i.e., analysis of alternatives) to support KPP assessment; this also relates to representations within system models. This use case also investigates the methods to trace capabilities to the relevant design disciplines and to perform cross-domain analyses through MDAO for problem and design tradespace analyses. In addition, to characterizing elements of the framework, cross-domain relationships, but also characterize the methods used to support MDAO in a tool independent manner.

MDAO is an approach for calculating optimal designs and understanding design trade-offs in an environment that simultaneously considers many types of simulations, evaluations, and objectives. For example, when designing an air vehicle, there is typically a trade-off between maximizing performance and maximizing efficiency, where calculating either of these objectives require multiple disciplinary models (geometry, weight, aerodynamics, propulsion). MDAO prescribes ways to integrate these models and explore the necessary trade-offs among the objectives to make a design decision. While the theoretical foundations of MDAO are well-established by academics, a number of barriers to practical implementation exist. Chief among these is the lack of model integration, which prevents designers of one subsystem from easily assessing how changing a design variable affects the results of other subsystems' models or simulations.

As illustrated by some of the examples shown below, we can extract the key parameters in these various mission and system simulations. These parameters are fundamental to the MDAO workflows. We need to combine those parameters for different elements of a workflow, but we must also characterize our KPPs; for example, a surveillance UAV range or endurance (e.g. number of hours of flight) would be examples of possible KPPs. These KPP are modeled as the outputs from running the MDAO through different optimizations. The other aspect of the method involves identifying the constraints that must be characterized with respect to KPPs (i.e. outputs) with respect to selected inputs.

4.1 MDAO Objectives

The following provides more specific objectives for MDAO use:

- Assessing the impacts of individual design changes on system capabilities
- Supporting early-phase (conceptual design), system-level trade-off analysis using previous evaluation results from existing models
- Develop strategies to transform the contracting process so that RFPs can be designed more flexibly toward value-based (rather than target-based) design

In pursuit of these objectives, the research activities entail:

- Develop generic multidisciplinary models of NAVAIR-relevant system examples, including analyses of the geometry, structure, aerodynamics, propulsion, stress, thermal and performance capabilities, to be used as an example case
- Investigate MDAO architectures such as multidisciplinary feasible and interdisciplinary feasible to compare simulation results when searching for optimized solutions [48][49]
- Explore using systems representations (e.g. SysML, Domain Specific Models) to map all inputs (parameters and variables) and outputs (objectives, constraints, intermediate parameters) among the individual models
- Conduct trade studies on the UAS design using established approaches and tools for MDAO, exploring different approaches, tools, and visualization techniques to most effectively display information and uncertainty for decision-makers
- Explore ways that previous trade study results on detail-phase product design can be useful toward new conceptual design of products with varying mission capability requirements
- Use the surrogate pilot to understand the barriers to implementing this type of MDAO, culturally and practically/theoretically
- Explore more general ways to map and coordinate subject matter experts (SMEs) and data, models, and meta-models for improved requirements setting for RFP or CONOPS, and value-driven design
- Explore the ways that MDAO and MBSE tools can work together

One of the objectives of this use case is to leverage the most powerful tools that are often used by industry as well as government organization. We have secured academic licenses to Phoenix Integration's ModelCenter [146]. Further, while research to date examines the use of MDAO at the systems level. We have received additional academic licenses to ModelCenter to investigate the use of MDAO at the mission and subsystem levels. However, based on the concept of the SET Framework, MDAO analysis at the subsystem level will probably be carried out by industry that is developing the designs.

4.2 MDAO Methods

Using tools like ModelCenter, we have investigated, demonstrated and described methods for applying such tools, and also identified relevant research questions in the context of those advanced tools. For example, the steps for an MDAO method may be characterized as:

- Describe a workflow (scenarios) for a KPP (e.g., range, notionally similar to surveillance time)
- Determine relevant set of inputs and outputs (parameters)
- Illustrate how to use a Design of Experiments (DoE) and use analyses such as sensitivity analysis and visualizations to understand the key parameter to use with optimizations
- Illustrate Optimization using solvers with key parameters and define different (key objective functions – on outputs) to determine set of solutions (results often provided as a table of possible solutions)
- Use visualizations to understand relationships of different solutions
- Investigate MDAO architectures alternatives such as multidisciplinary feasible and interdisciplinary feasible to compare simulation results when searching for optimized solutions [48][49]

A number of methods can be applied to formulate multidisciplinary optimization problems, develop useful surrogate models, and calculate optimal and Pareto-optimal solutions. Optimization problems can be formulated with a number of different objectives by converting some objectives to targets or constraints, summing the objectives with value-based and unit-consistent weighting schemes, or multiplying and dividing objectives by one another. Surrogate models are often used to quickly simulate the behavior of a more computationally-intensive simulation model, and some common methods include interpolation, response surface using regression models, artificial neural networks, kriging, and support vector machines. Finally, numerical optimization can be performed using a number of different algorithms and techniques, including gradient-based methods, pattern search methods, and population-based methods. For each of these, different techniques have been found to be more suitable to different applications, and part of this research directive will be to identify and demonstrate the best tools for this MCE architecture.

4.3 Integrations with Related Tasks

Through this project, and the creation of an MCE architecture that follows an AST and a consistent ontology, we investigate how to leverage MDAO techniques in the design decision-making process. A solid framework for MDAO can enable multi-objective optimization, showing product developers how different design objectives compete with one another. For example, we know that improving an objective like “minimize weight” typically requires a sacrifice in the objective to “maximize power.” The magnitude of that improvement-sacrifice relationship, which often involves different units and requires human judgement to make a mission-appropriate decision, can be revealed by combining different simulation models, surrogate models, and optimization routines. As this may involve balancing a large number of objectives, one of the key challenges is in visualization of the results to enable informed decision-making. This fits into all five tasks of the project, as the entire information architecture must be built to support cross-disciplinary analysis, and specific tools and techniques can be integrated and tested at different stages of the transformation.

4.4 MDAO UAV Examples and Use Cases

Examples and demonstration covering several of the objectives have been presented in several working sessions as well as several bi-weekly status meetings and at several events such as the Phoenix Integration International Users' Group [22]. We have five use cases:

1. Developing MDAO workflows for KPP examples at system level
2. ModelCenter integrated with a Graphical Concept of Operation (CONOPS) example using Unity gaming engine at the mission level
3. Integrating MagicDraw SysML models with ModelCenter and MBSEPak for an underwater super cavitating modeling system
4. ModelCenter and MBSEPak, with MagicDraw SysML to formalize the concept of an Assessment Flow Diagram, which is part of the Decision Framework and process [52]
5. ModelCenter and MBSEPak, with SysML for two-Degree-of-Freedom (2DOF) for the surrogate pilot design

This section provides a summary of some of the evolving use of MDAO in our research.

4.4.1 MDAO Example for Fixed Wing UAV

The first demonstrated workflow shown in Figure 33 was developed using ModelCenter. This demonstration covered several aspects of the modeling objectives discussed in this section, including:

- Describe and execute a workflow analysis of UAS capabilities (e.g., range, velocity, and fuel consumption)
- Map relationships among parameters (inputs/outputs) in disciplinary models
- Illustrate use of Design of Experiments (DoE), sensitivity analysis, and visualizations to understand capability relationships/trade-offs
- Optimize using different solvers to find sets of Pareto-optimal solutions
- Take advantage of previous model analyses for use in early-phase design with new mission capability requirements

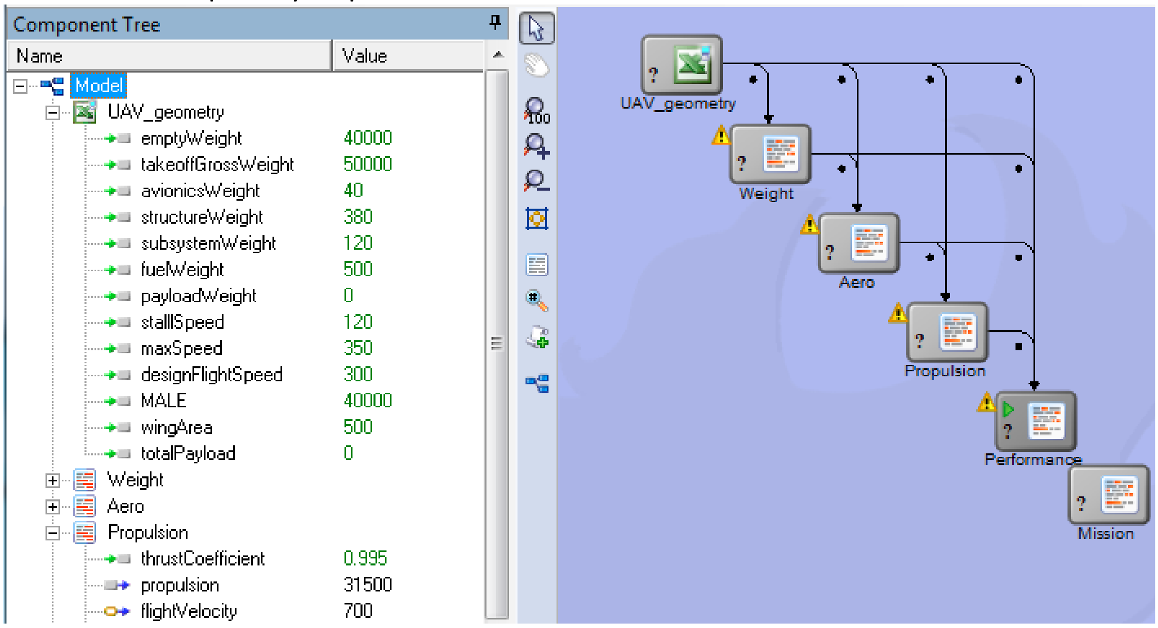

Figure 33. MDAO Example Workflow

As shown in Figure 34, the Pareto frontier (Pareto optimal set) shows the trade-off between range and propulsion. The blue points show the Pareto frontier/non-dominated solutions. The Pareto frontier was calculated using a bi-objective optimization using NSGA-II algorithm to:

- Maximize range
- Maximize propulsion
- Given 5 design variables
  - Wing area (ft2)
  - Wing span (ft)
  - Altitude (ft)
  - Speed (knots)
  - Efficiency factor

These results reflect on how much range one would have to give up in order to increase the propulsion by some amount. Based on the current set of equations characterized in the workflow, the sensitivity analysis shown in Figure 35 indicates that the wing area is the variable that exhibits the clearest trade-off. The wing span has the largest effect on range, but does not present a trade-off between these objectives.

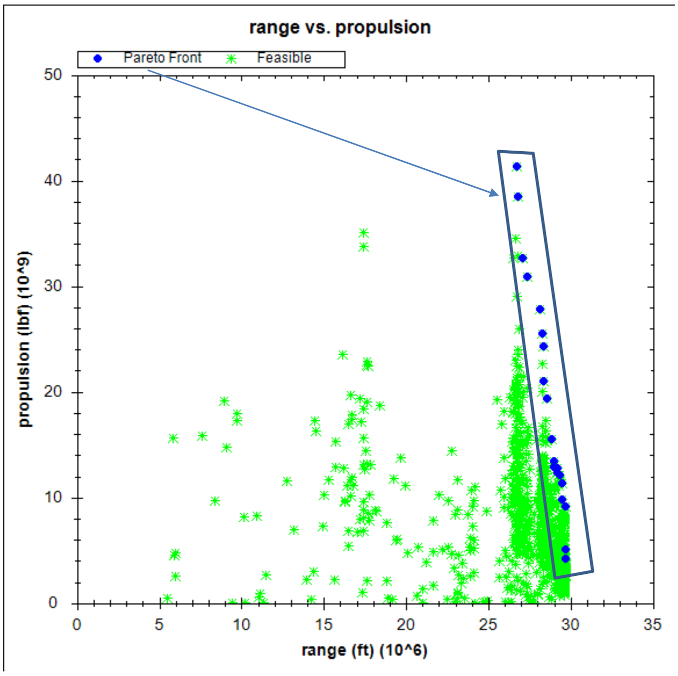

Figure 34. Pareto Frontier (Pareto Optimal Set) Shows Trade-off Between Range and Propulsion

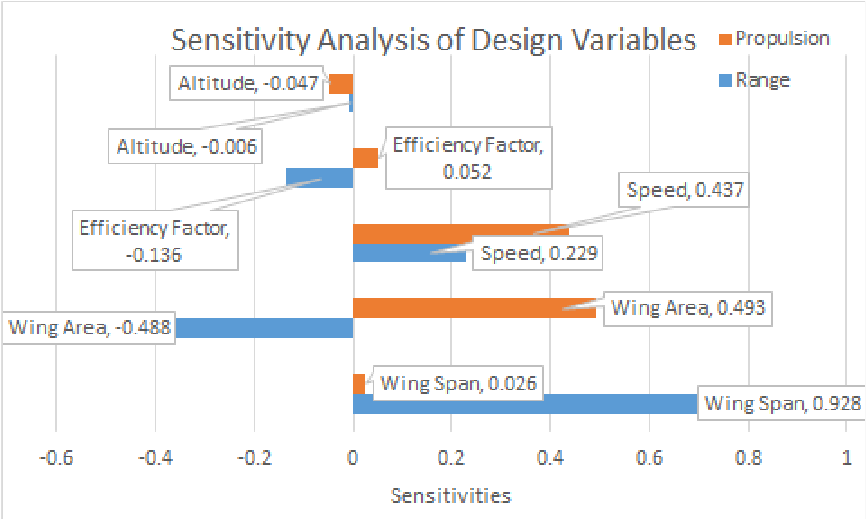

Figure 35. Sensitivity of Objectives to Design Variables

4.4.2 Extending the MDAO UAV Example 1

Brian Chell is a PhD student working with Dr. Steven Hoffenson produced alternative workflows that leverage other types of solvers for different aspects of the problem including multi-physics problems. For example, one of the first steps looked at bringing SolidWorks into ModelCenter as shown in Figure 36. This provides a way to bring in detailed geometries to the analysis.

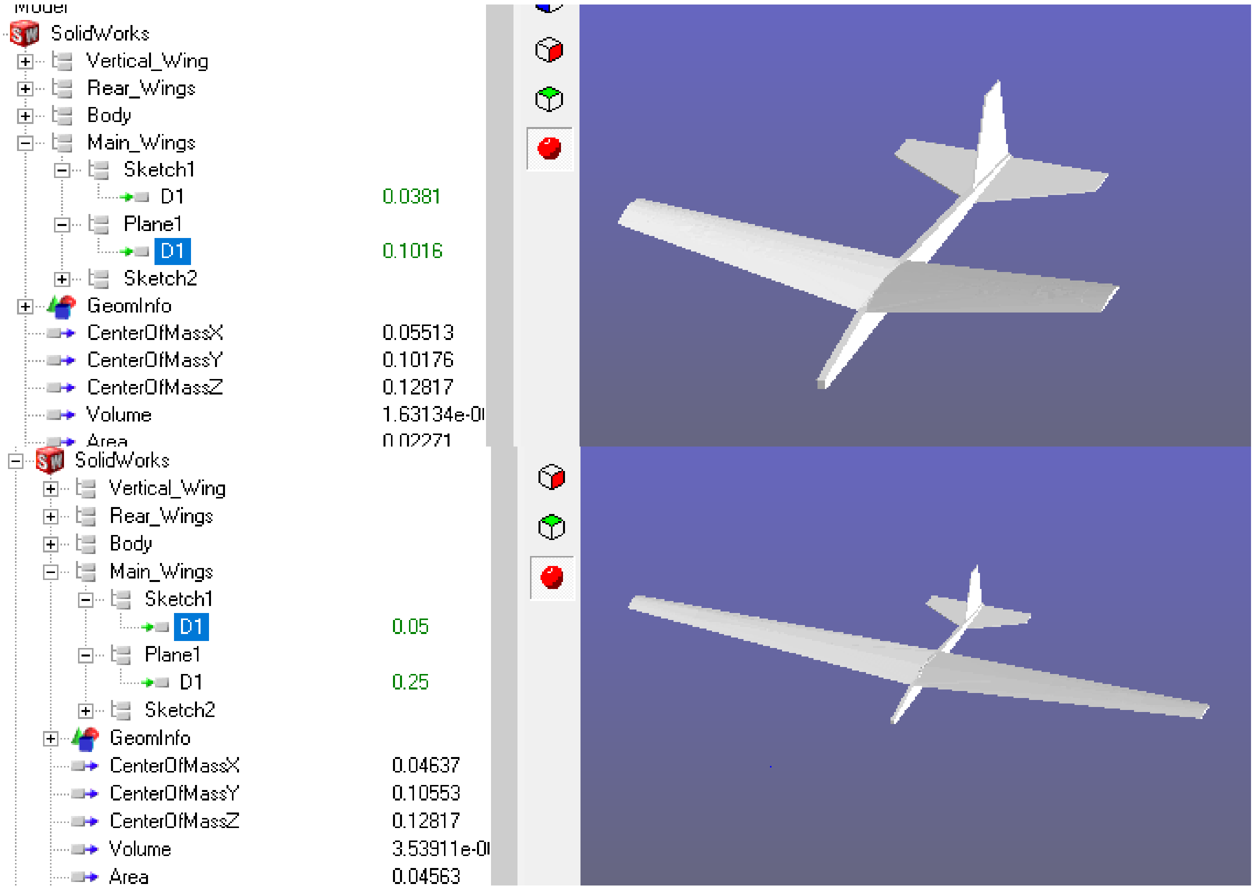

Figure 36. MDAO Workflow with SolidWords Computer Aided Design Model

There were a few challenges with the more complicated geometries, as well as:

- Open-source geometry validity is questionable
- Model variables
    - Most SolidWorks files found so far do not import variables into ModelCenter automatically
    - We assume that we can set the variables within SolidWorks, but this might be more difficult because manually setting values may not align structures (e.g., wing connect to fuselage to meeting correct)
- More complex
    - Computations solver (e.g., CFD) take longer to run on the laptops provided to students

This has led to the following investigations:

- Equation-based models derived from the model shown in Section 4.4
    - Uses DLR Institute's Unmanned Combat Air Vehicles (UCAV) [111] parameters
    - Model is fully operational
    - Based on weight fractions that are more scalable, and easier to change than DLR UCAV model
    - Model starting with payload weight vs. range vs. endurance tradeoffs
    - Looking at the potential to merge with future CFD results with Finite Element Analysis (FEA)
- Simulation-based models
    - Difficulties
        - Still problems with importing variables into ModelCenter
        - Very large number of variables automatically imported (12,000+)
        - Under construction
    - Consider open source simulation OpenVSP [140] vs. Solidworks (CFD)
        - OpenVSP is a parametric aircraft geometry tool
        - OpenVSP allows the user to create a 3D model of an aircraft defined by common engineering parameters. This model can be processed into formats suitable for engineering analysis.
        - OpenVSP commonly used with ModelCenter
        - SolidWorks has stronger analysis capabilities
        - OpenVSP is limited to a standardized shape library
        - SolidWorks Flow Simulation can handle turbulence
        - OpenVSP CFD is most valid at nominal flight conditions (e.g. low angle of attack)
        - OpenVSP should be sufficient for conceptual design phase

OpenVSP is being used for CFD. It is easier to use with limited library of shapes of quadcopters and fixed wing, and can run 'headless' (i.e., without GUI) to make computations less expensive. NASA has been using this with ModelCenter. The current status is:

- Integrated parametric geometry and CFD into ModelCenter
- Performing optimization and DOE to characterize model
- Trying to find lowest-fidelity mesh that produces accurate results
- Challenges:
    - Takes some time to change between different aircraft
    - Future NASA wrapper will make this much easier

- High-fidelity CFD simulations are very slow on low-end laptops like those provided to students; need to determine if Stevens and provide higher performance computing resources

Figure 37 show the CFD results from the same geometry under the same flight conditions with different fidelity meshes. The simulation on the left has a coefficient of lift many magnitudes higher than the one on the right. Investigate mesh balancing accurate results and low computing cost.

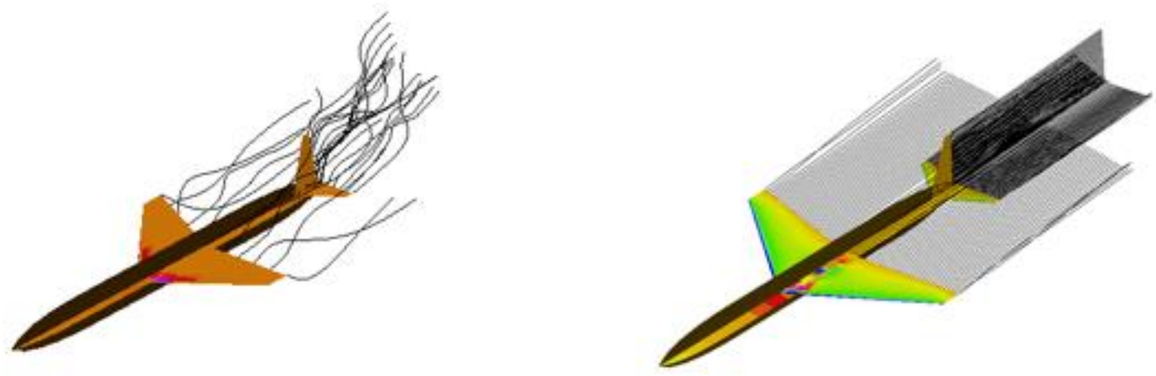

Figure 37. CFD Mesh Fidelity Importance

Updates to the first model include analysis for both CFD and FEA with the objective to maximize endurance and range, and minimize stress at every span-wise node. This is done with another workflow as shown in Figure 38, with the resulting aircraft shown in Figure 39.

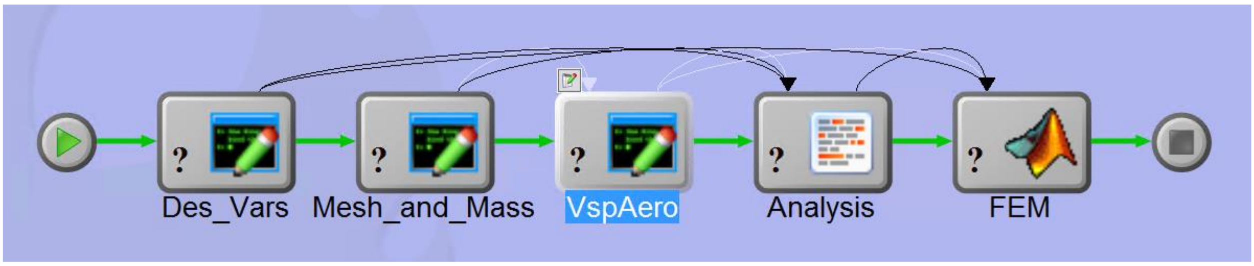

Figure 38. Update MDAO Workflow including CFD and FEA

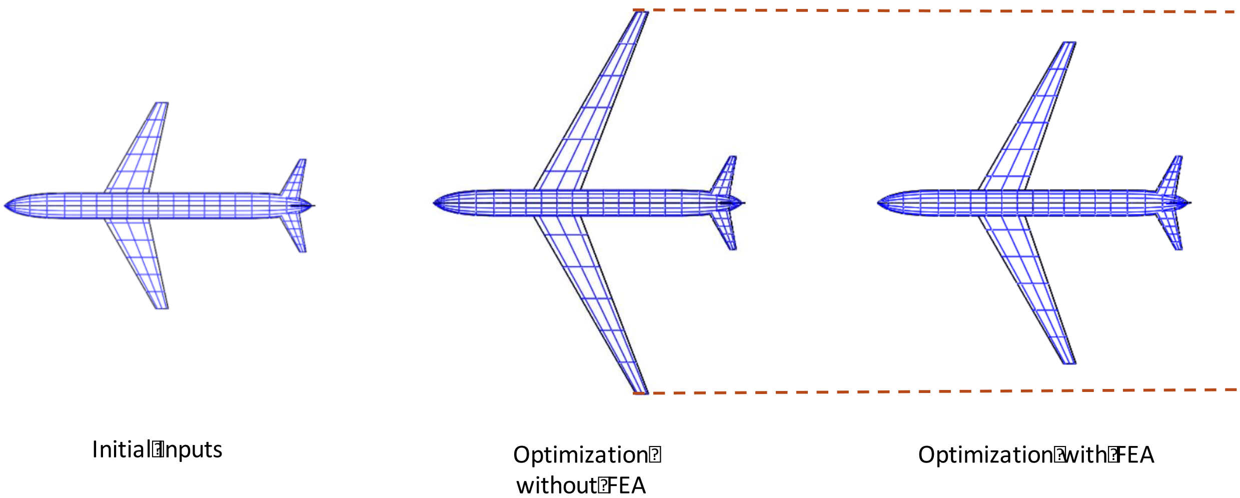

Figure 39. Resulting Aircraft Designs with and without FEA

4.5 MDAO AT THE MISSION LEVEL USING GRAPHICAL CONOPS

This use case investigates an extension of the prior work to using the Graphical CONOPS technologies Unity gaming engine with MDAO using ModelCenter. The MDAO methods used:

- Design of Experiments (DoE) to run the simulation over the entire range of every input variable
  - Choose an appropriate DoE sampling method to shorten run time
    - Full Factorial
    - Latin Hypercube
- Sensitivity Analysis
  - Find which outputs are most sensitive to which input variables
  - Can remove (or fix the value) of non-sensitive variables to save time during optimizations
- Optimization
  - Use algorithm to optimize desired objective(s)

While there were challenges that were overcome, the experiment demonstrated that it is possible to use MDAO to optimize for mission success, and the number of experiments (runs) to cover the DoE space of 1000s cases versus 10s of cases that would be covered by running the scenarios manually.

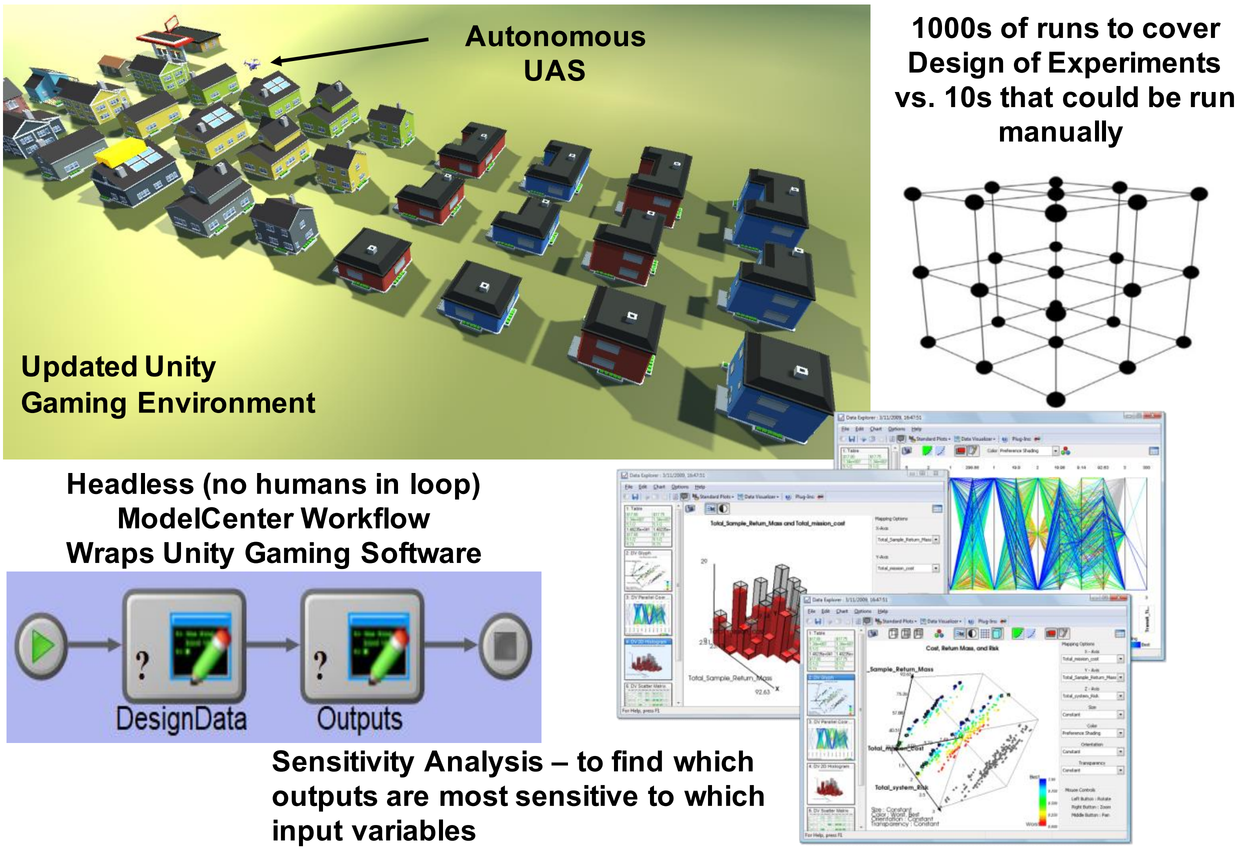

Figure 40. Explore the Integration of Graphical CONOPS Simulation with MDAO Tools

The capabilities focused on objectives to understand and overcome the challenges for a fully automated MDAO at the Graphical CONOPS level, including:

- Performance is measured by degree of success of a mission
- Artificial Intelligence (AI) is applied to counterparties so that they can adapt to and learn behavior of system
- Full automation – there was no humans in the loop, except for validation of behavior
- Simulated environment that includes counterparties was observed to behave in a surprising manner (e.g., there was emergent behavior)
- Software communicates programmatically through file transfer – as opposed to being directed manually
- Monte Carlo results in thousands of runs (vs. 10s when run manually) are made for each initial state to provide statistics
- Simulation can run at high speed to maximize statistics and in real time to allow for human validation of simulation behavior

The finding suggests that MDAO can be used to optimize for system-level mission success to study far more trades than can be performed manually. The initial attempt created the simulation and removed the CONOPs visualization using a "headless" simulation that is wrapped by ModelCenter. Initially the architecture of the simulation was not enabled to operate in batch modes, and therefore the software had to be re-written to work with ModelCenter. When the simulation is running, the human cannot make edits, but the re-written and wrapped simulation can run thousands of design of experiments (DoE). The initial simulation ran in real-time, but a recent update now can run faster than real-time.

4.6 Formalizing Assessment Flow Diagrams as MDAO Workflow

For populating the Decision Framework [52] as discussed in Section 3.6, we collected all of the elements of information from a populated SysML model. The research objective is to determine how/where to collect all of the information reflected Figure 42 from rigorously specified models about alternative analysis for a set of small UAVs. The underlying computations are publicly available. This allowed us to perform most of the computation directly on the data stored in a triple store, and then extract information directly for the visualization. These types of visualization provide senior leaders and program managers the type of information they need to consider technology capability tradeoff using Performance, Cost (Affordability), Time (delivery schedule) and Risk, as shown in Figure 41.

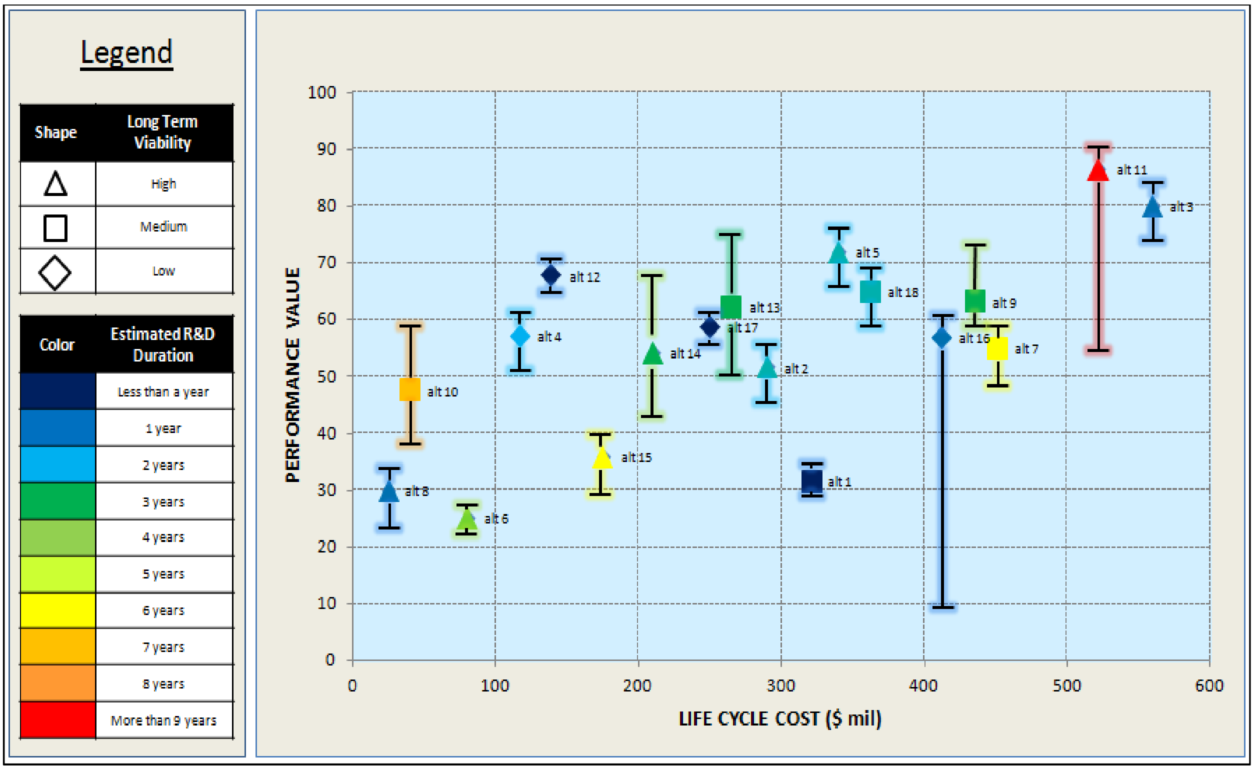

Figure 41. Visualizing Alternatives – Value Scatterplot with Assessing Impact of Uncertainty

Fundamentally, if a particular answer was unacceptable, using the concept discussed herein, we could trace linkages through the underlying information model back to all other related perspectives on the system in terms of operational, mission, system, and subsystem design alternatives and trades. These elements would include:

- Objective hierarchies
- Value functions
- Assessment Flow Diagrams (AFDs) trace the relationships between physical means, intermediate measures, and fundamental objectives
- Uncertainties

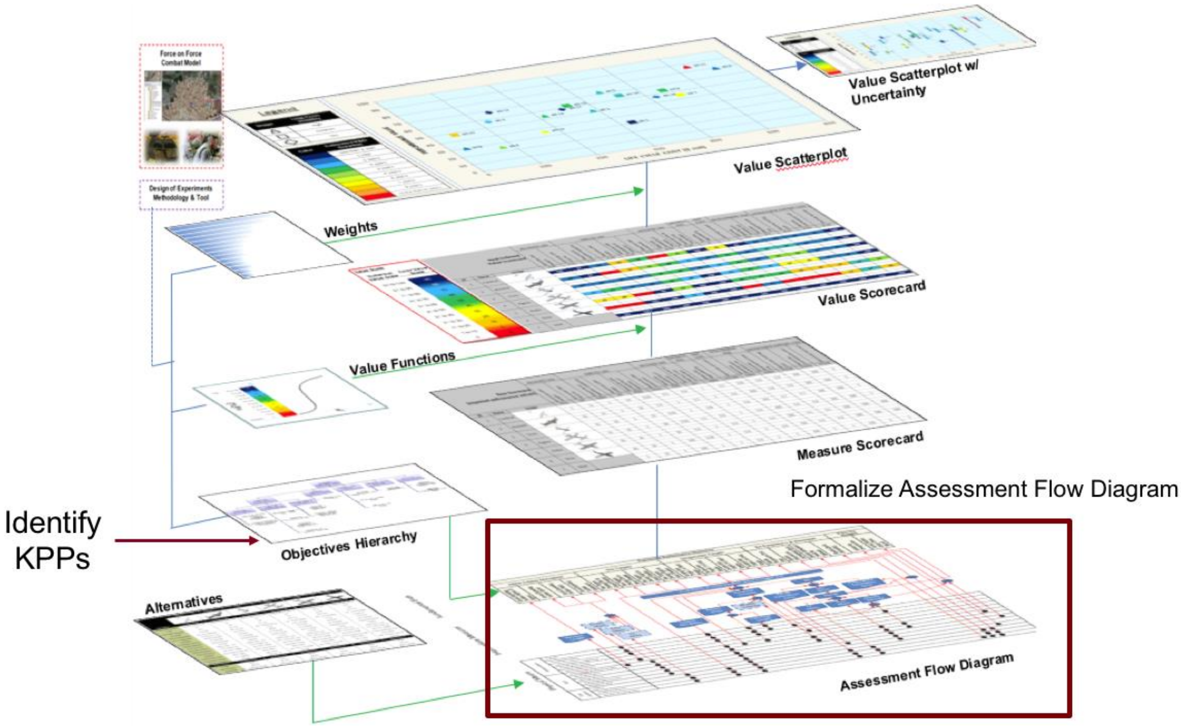

Figure 42. Decision Support Model Construct

We successfully formalized the AFD using SysML, which was previously done in PowerPoint, as shown in Figure 43. This research demonstrated that we can formalize the AFD in SysML and be transformed into an MDAO workflow. We started with SysML and used the MBSEPak to produce the MDAO workflow.

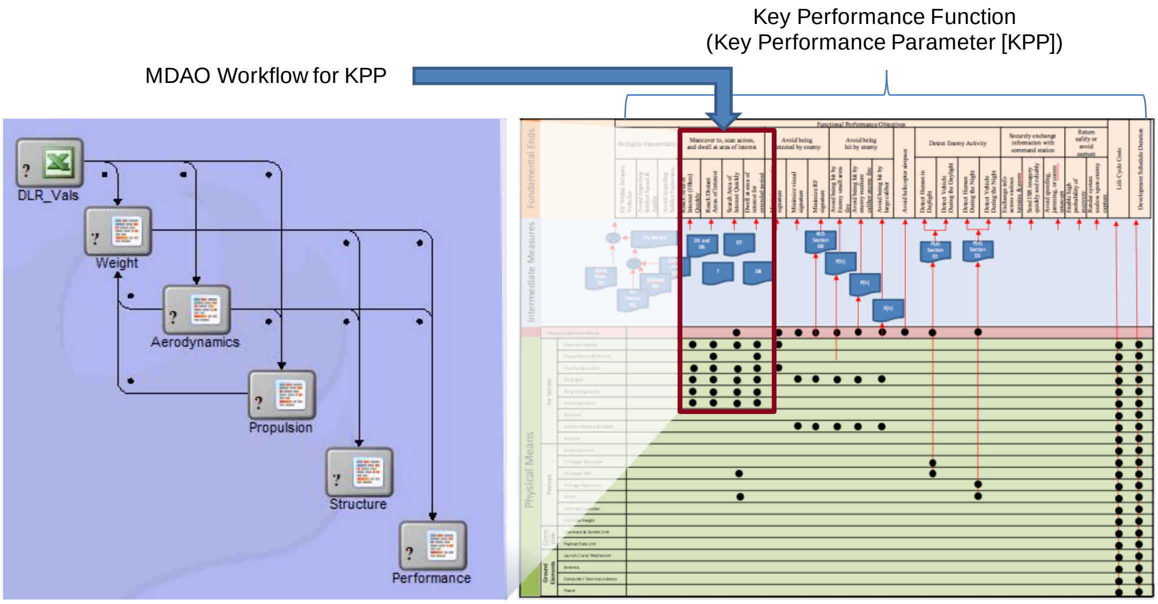

Figure 43. Formalizing the Assessment Flow Diagram

These results formalized the representations of AFD using SysML, MBSEPak and ModelCenter, because the KPPs can be mapped to one or more MDAO workflows as reflected in Figure 43, with some recommendation modeling practices that are needed when using MBSEPak with SysML from Phoenix Integration. A Webinar explaining this approach is provided at the Phoenix Integration website (https://www.phoenix-int.com/learn-

more/webinars/) called "Applications for Three Research Use Cases in Model Centric Engineering using ModelCenter and MBSEPak."[21] For additional details, see Appendix C.

The modeling steps follow from the Decision Support Construct:

1. Model system structure in SysML
2. Model as derived value types in SysML decomposition
3. Add the needed Measure scorecard that contains the Metrics of interest in the analysis
4. Value scorecard provides basis to compare metrics as perceived by user

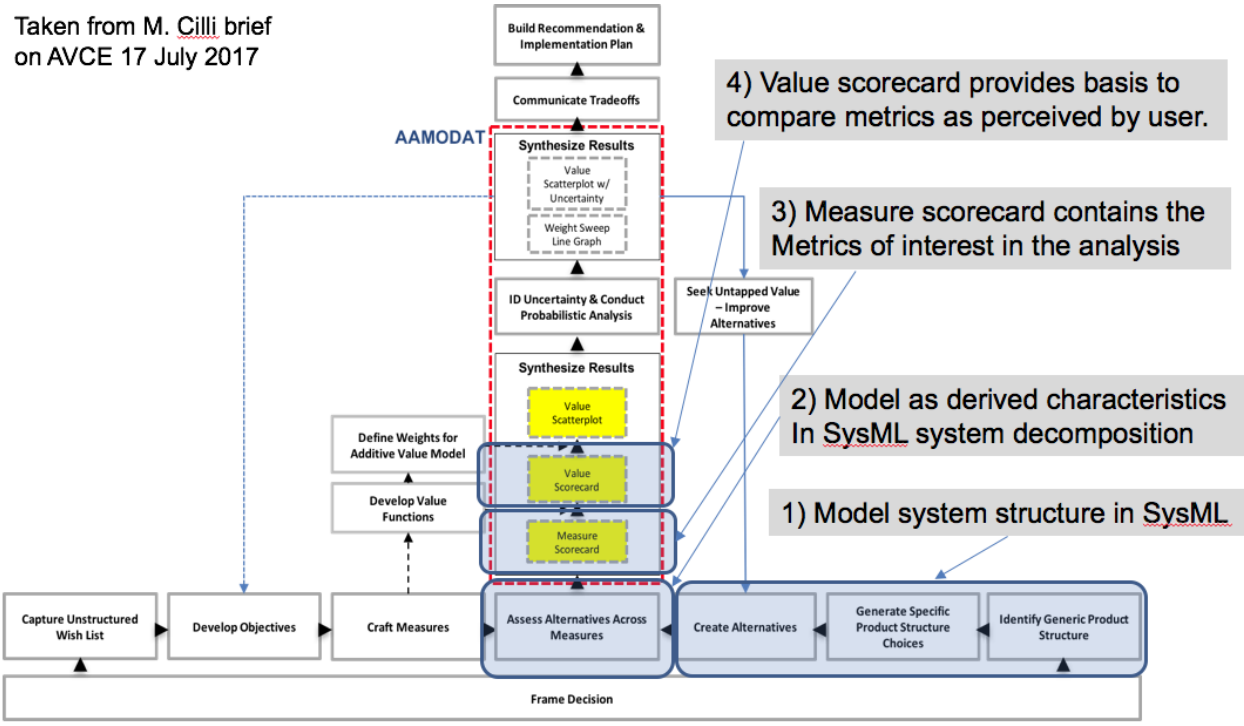

Figure 44. Decision Support Model Construct

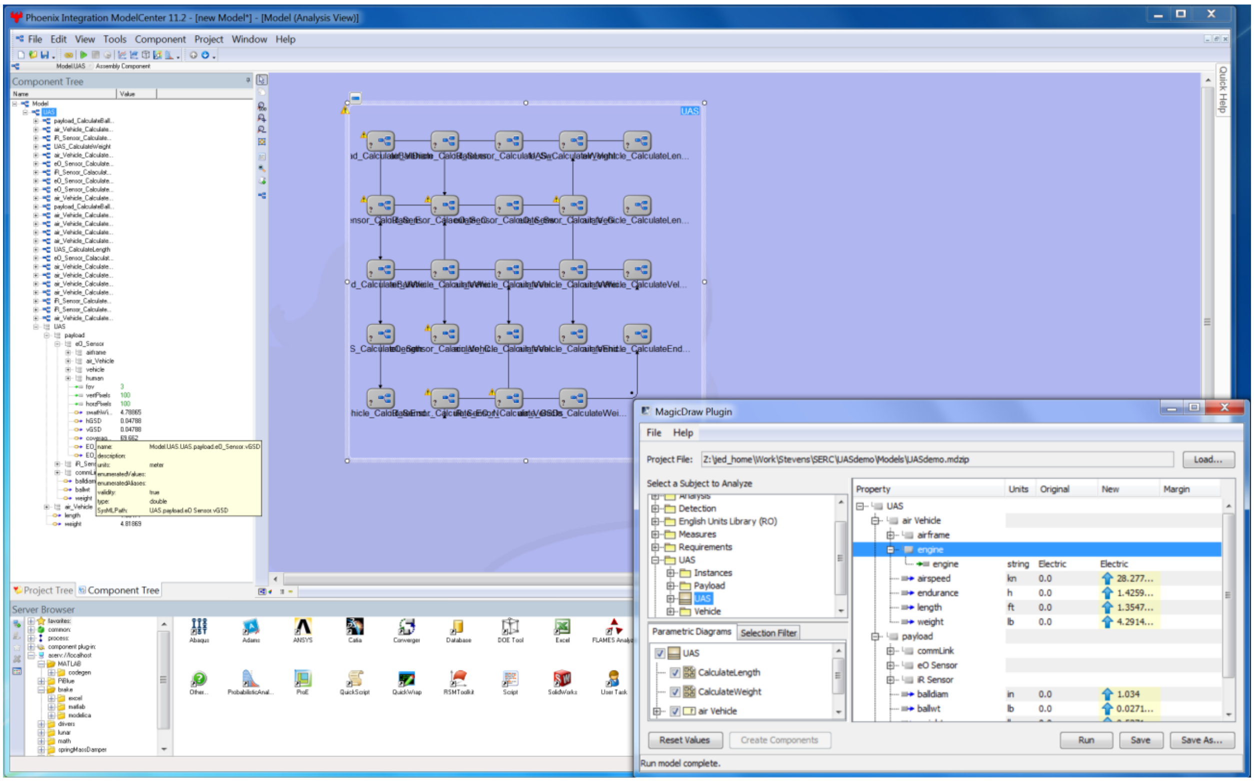

Figure 45. MBSEPak Creates Analysis Workflow and Checks Data Type Consistency

4.7 SURROGATE PILOT CONTRACTOR MDAO ANALYSIS FOR DESIGN

This section provides another example for the use of MDAO. Figure 46 illustrates the use of MDAO using ModelCenter that links to a two-Degree of Freedom (2DOF) dynamics model in Activate [5]. Activate supports modeling and simulating of multi-disciplinary systems in the form of 1D models (expressed as signal-based or physical block diagrams) that can be coupled to 3D models.

Our Surrogate Contractor team used MagicDraw starting from the GFI model provided by the government system modeling team with MBSEpak to create a constraint for endurance, that links to Activate. The surrogate design passes design variables (cruise speed/empty weight/rotor performance) into Activate model and returns endurance/fuel economy output from Activate model back into the MagicDraw, and it saves the output (endurance) in the system model.

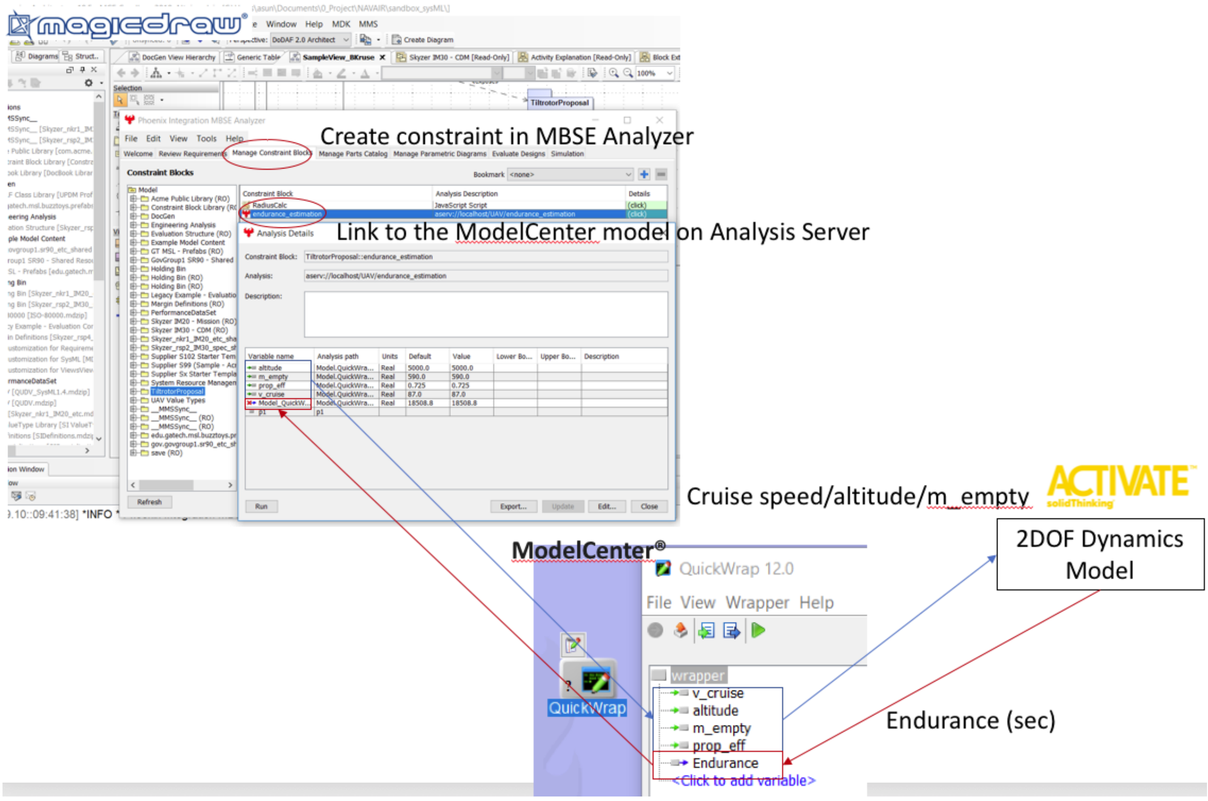

Figure 46. Surrogate Contractor MDAO Analysis[20]

5 UC02: Integrated Modeling Environment (IME)

This use case investigates topics for Integrated Modeling Environments (IMEs) with specific focus on creating and collaborating in an Authoritative Source of Truth (AST) for the surrogate pilot in the context of the research thrusts. Many of the details for this use case are discussed in Section 2.4, and in the broader set of capabilities to integrate OpenMBEE, SysML tools, MDAO tools, Visualization tools, with IoIF as shown in Figure 31.

The descriptive modeling tools used to develop SysML models for the surrogate pilot, which are committed to MMS and synchronized to Teamwork Cloud are represented in Figure 47 [109]. The specific tool versions are: Magicdraw and Teamwork Cloud v. 18.5 SP3, MMS v. 3.2.2, View Editor v. 3.2.1 and MDK v. 3.3.6. These products were used only for demonstration purposes. The use of these tools does not imply any approval or endorsement by our sponsor.

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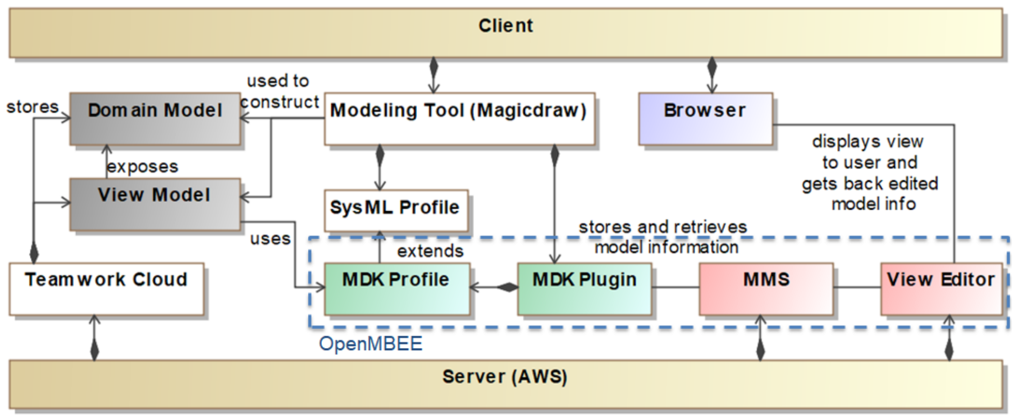

Figure 47. OpenMBEE Environment Implementation

6 UC03: Modeling Methods

This use case investigates the development and demonstrations of methods for technologies in the context of the IME workflows, such as:

- Methods for mission model
- Methods for system model
- Methods for modularizing models to support constraints needed for developing an authoritative source of truth, which relates to many other use cases
- Methods for model management
- Methods for representing and organizing reference models, process models, discipline-specific models
- Methods for MDAO modeling are discussed in Section 4
- Methods for traceability
- Alternative approaches to improve modeling methods, which is fundamental to ensuring model integrity
- Preliminary approaches for embedding digital signoffs within models

6.1 Mission Model

The approach for developing the mission model is based on an Integrated Capability Framework (ICF) Operational Concept Document (Version 3.2) 22 February 2016. This document is considered "Distribution D," which means it may only be available to companies that are doing business with the government. The initial Skyzer Mission model is available publicly on the AWS server. This approach demonstrates that modeling can be used and comply with existing standards that traditionally have been document-based.

The guidelines include:

- Thoroughly define required mission capabilities, measures of effectiveness, and associated operational conditions and constraints.
- Identify System of Systems (SoS) interfaces and measures of performance through structured decomposition of required mission capabilities.

- Provide a common, cross-Systems Command (SYSCOM)/Program Executive Office (PEO) framework to facilitate enterprise level engineering across the SYSCOMs and enable efficient system integration and effective force interoperability.
- Establish enterprise data structures and implementation guidance to enable iterative development of enterprise architectures
- The consistent implementation of ICF practices and guidance across assessments and stakeholders supports:
  - A common understanding of mission requirements and a structured process to identify and align systems and platforms capabilities to support missions.
  - System and platform owners with a thorough set of interoperability requirements and knowledge of what platforms, interfaces and behavior to which they need to design, along with associated standards.

We have a View and Viewpoint hierarchy that extracts information from the Skyzer Mission model to "generate a specification," which aligns with the guidelines of the ICF. A portion of the View and Viewpoint hierarchy is shown in Figure 48. Note, for Phase 2, the mission model is to be aligned with the ASRM and the corresponding NAVAIR Systems Engineering Method (NAVSEM). An update View and Viewpoint hierarchy also aligns with the structure recommended by ASRM.

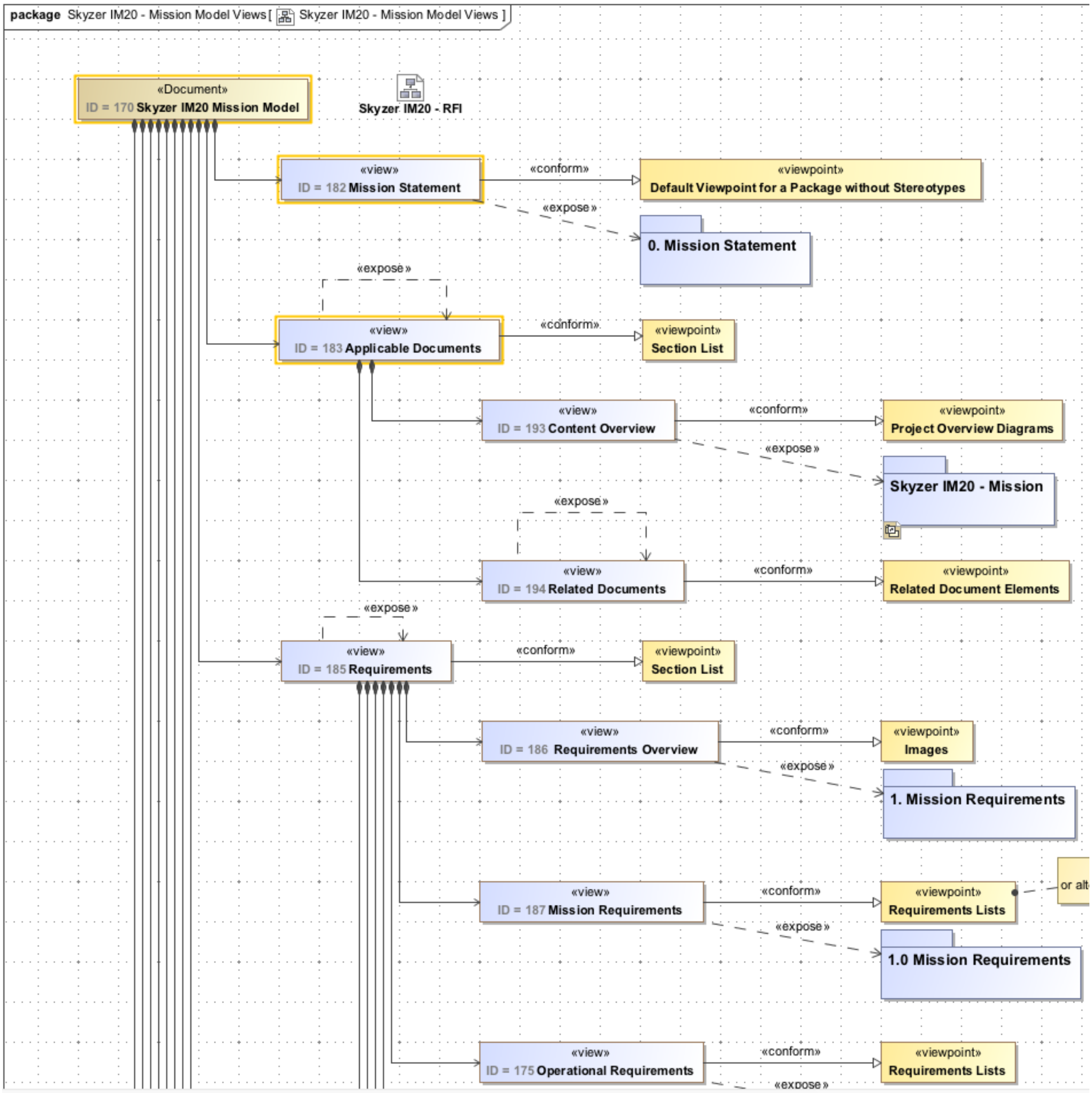

Figure 48. View and Viewpoint Hierarchy for Surrogate Pilot Mission Model

6.2 System Model

NAVAIR decided to adopt Object-Oriented Systems Engineering Method (OOSEM) [77] as the default for System Modeling using SysML and now is moving to NAVSEM for the system model as well as the mission model. There are many resources available that describe OOSEM. The main activities have been captured as a reference model. An example of is shown in Figure 49.

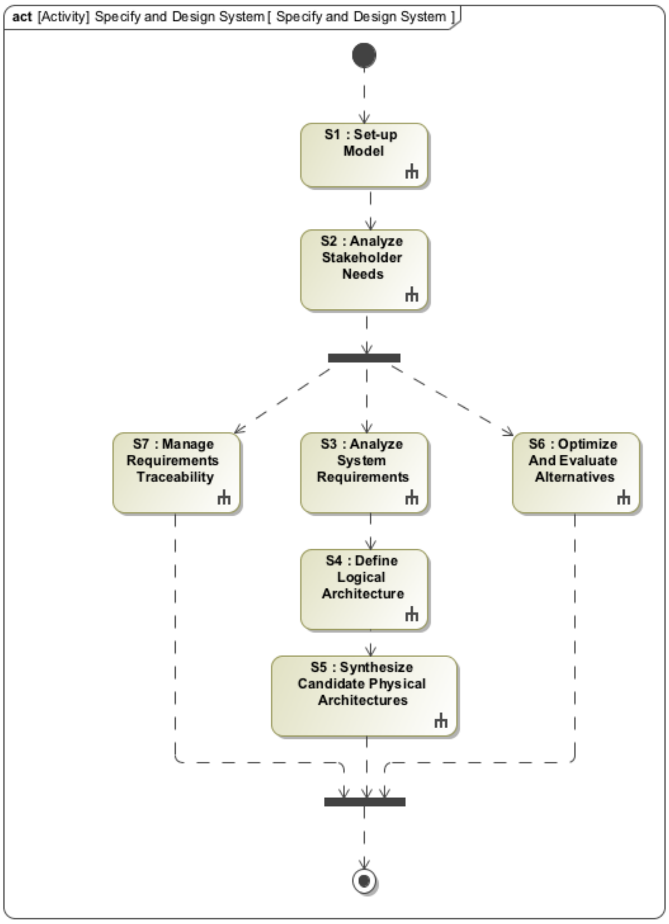

Figure 49. OOSEM Top Level Activities

6.3 MODULARIZING THE SYSML MODEL

The method for modularization models is also an important part of our surrogate pilot effort. As shown in Figure 50, we are using an approach for modularizing the surrogate pilot model that uses a "model reference" (Project Usage) concept so that the mission, system and other models can be created independently, but could be referenced in an overarching project/program model. Project usages provide a means for accessing shared elements of the used project. For example, in the containment tree on the left side of Figure 50, there are some packages, (e.g., Enterprise, Reference Models) that are in normal black font, but two models the Mission Level and System Level are slightly "grayed out," because these projects are references to separate models. In doing this, we can allow the Mission model and System model to be developed and updated separately, but when brought into the higher-level project model, we could view the entire model. In addition, as shown in the View and Viewpoint hierarchy, we can include these referenced models in one or more Views with Viewpoints, where DocGen can then generate a document or specification for the entire project or a subset of elements from various models. This concept of modularization would apply to other process models, such as those developed by competencies and reference models. We are investigating this evolving method, because it plays heavily with model management including tradeoff for both the Teamwork Cloud and OpenMBEE MMS. Finally, the project usage mechanism can be used to reuse elements from model libraries, such as the DocGen Viewpoints.

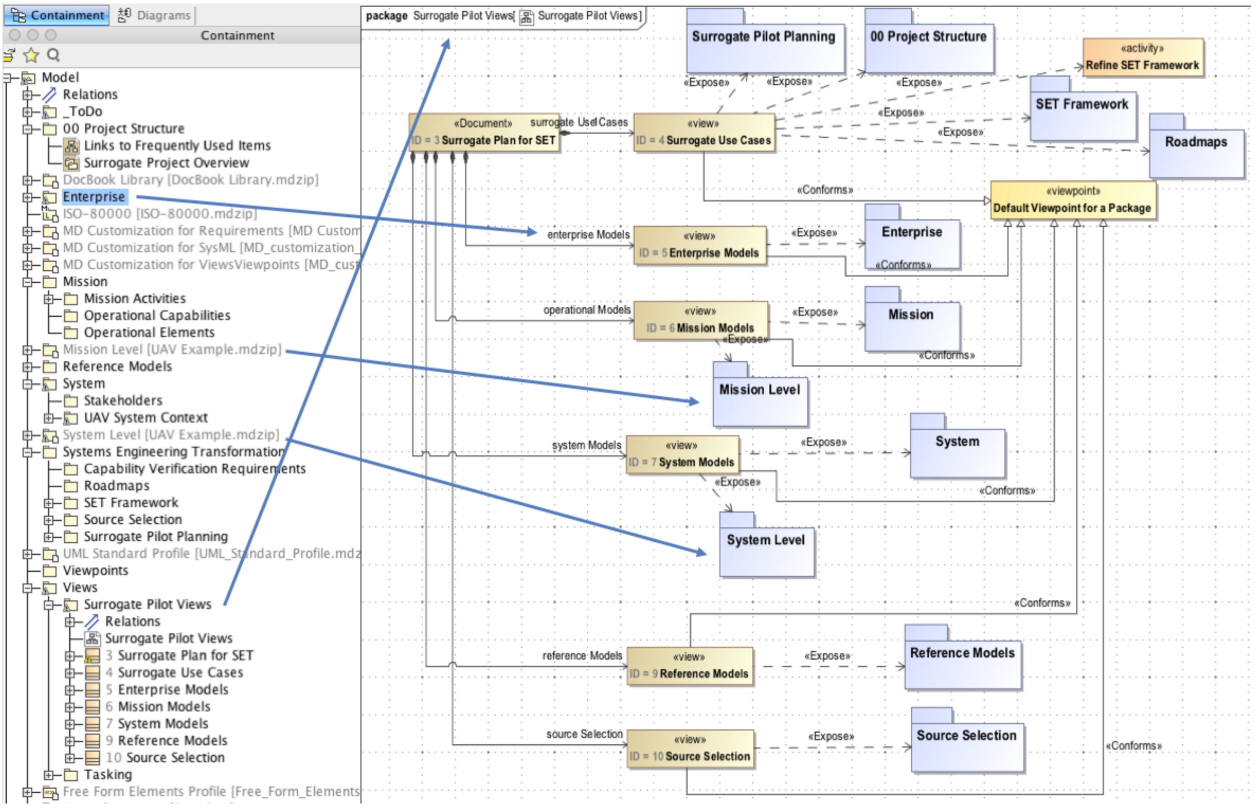

Figure 50. Modularizing Surrogate Pilot Model

A simplified excerpt of the project usage relations of the surrogate pilot with its separated view and domain models is shown in Figure 51. The composition relations represent project usage. The white domain models on the bottom use each other for traceability. They themselves are used by the view models to be exposed in view hierarchies, which requires the viewpoints from the used Viewpoint Library. The Issue Tracking model on the right again uses the two view models. The exemplary reviewer has full access on the Issue Tracking model and the Mission View Model, but read-only access on the Mission Model. That allows to edit and comment within the Mission View Model, without being able to directly change any exposed elements from the Mission Model. New issues can be created in the Issue Tracking model that reference any requirement or model object. Comments created in the Mission View Model can be directly inserted as issues, too.

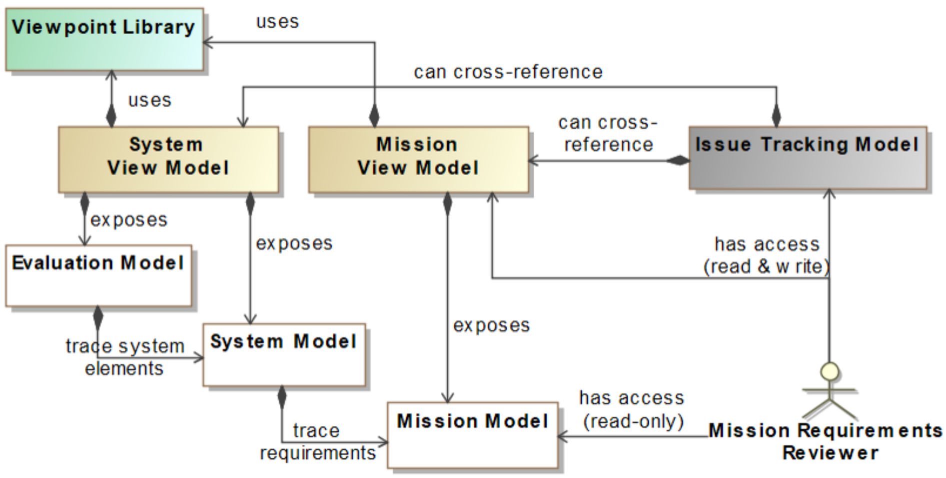

Figure 51. Example of Project Usage and User permissions for Mission Requirements Review

The ability to access elements from used projects allows traceability links, for example from UAV system elements back to specific mission requirements, which then can be exposed in the View Editor where model elements from used projects can be referenced. This is an important feature for the Issue Tracking model of the surrogate pilot. This model is fully handled in the View Editor with issues being created as class elements having a name and a description or by directly referencing existing comments created in documents of used projects. The description of an issue can also reference accessible model elements within the AST, for example, to link issues to impacted or problematic model elements. This again does not require detailed knowledge about the underlying models or SysML itself.

6.4 Views and Viewpoints

The basic elements, as shown in Figure 52 can be included within an overarching document, which includes:

- Document – the overarching model element
  - Document can include other documents, which also provides another level of modularization and support for reuse
- View (there can be one or more views in a document)
- A View uses the Exposes relationship to associate the View with some element in the model (e.g., Package, Diagram, etc.)
- View conforms to a Viewpoint
- Viewpoint defined using a special language created out of a profiled activity diagram that can collect, filter, and then produce a document through a DocBook standard

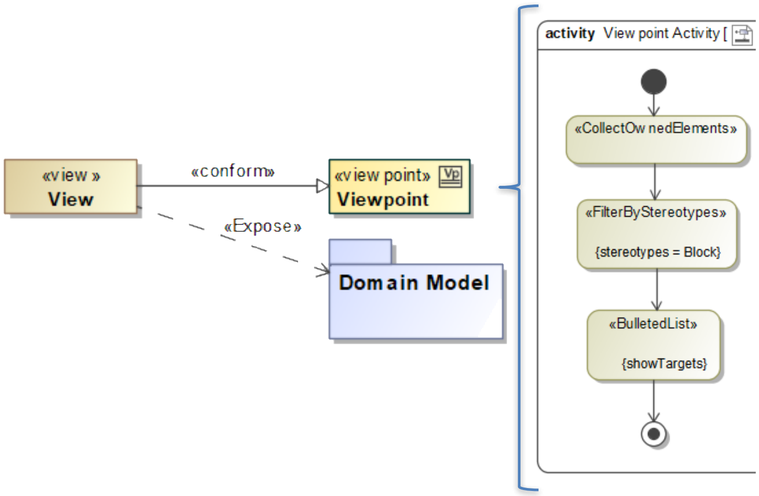

Figure 52. Element of View and Viewpoints

A document assembled from a number of Documents or Views can be generated into DocBook, which can then be generated into PDF, Word, HTML, and other formats. These Views can also be synchronized into the OpenMBEE MMS as shown in Figure 53. The View Editor can then be used to view the generated specification; in addition, it can export (generate) into Word, PDF, and HTML. The View Editor also allows for editing and updating a generated view that can also be pushed back into the MMS, as well as back into the model (for certain types of model elements).

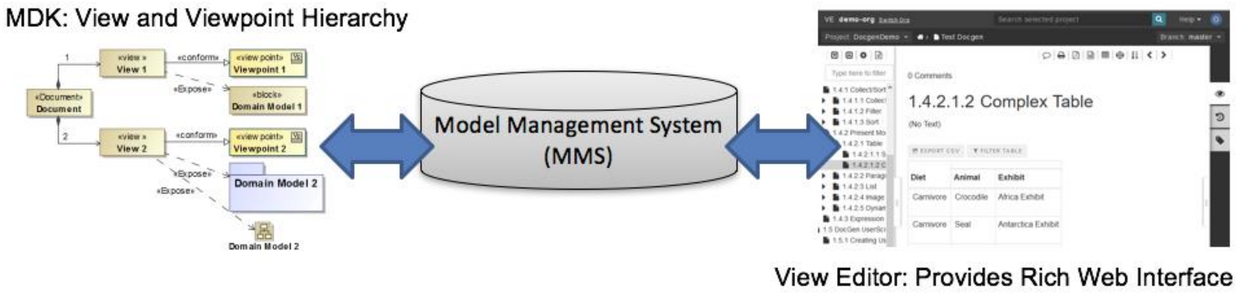

Figure 53. Views are Pushed into Model Management System and Viewable through View Editor

As shown in Figure 54, the View Editor runs in a standard web browser and lets users navigate the View hierarchy, and visualize specific Views within the hierarchy, edit the views and examine history associated with changes of the View. There are capabilities for branching those changes. This is part of the future research to investigate the combination of facets related to View and Viewpoint hierarchies, model management in MMS as well as in Teamwork cloud. We are working in conjunction with industry and our NAVAIR sponsors on the best methods for model management.

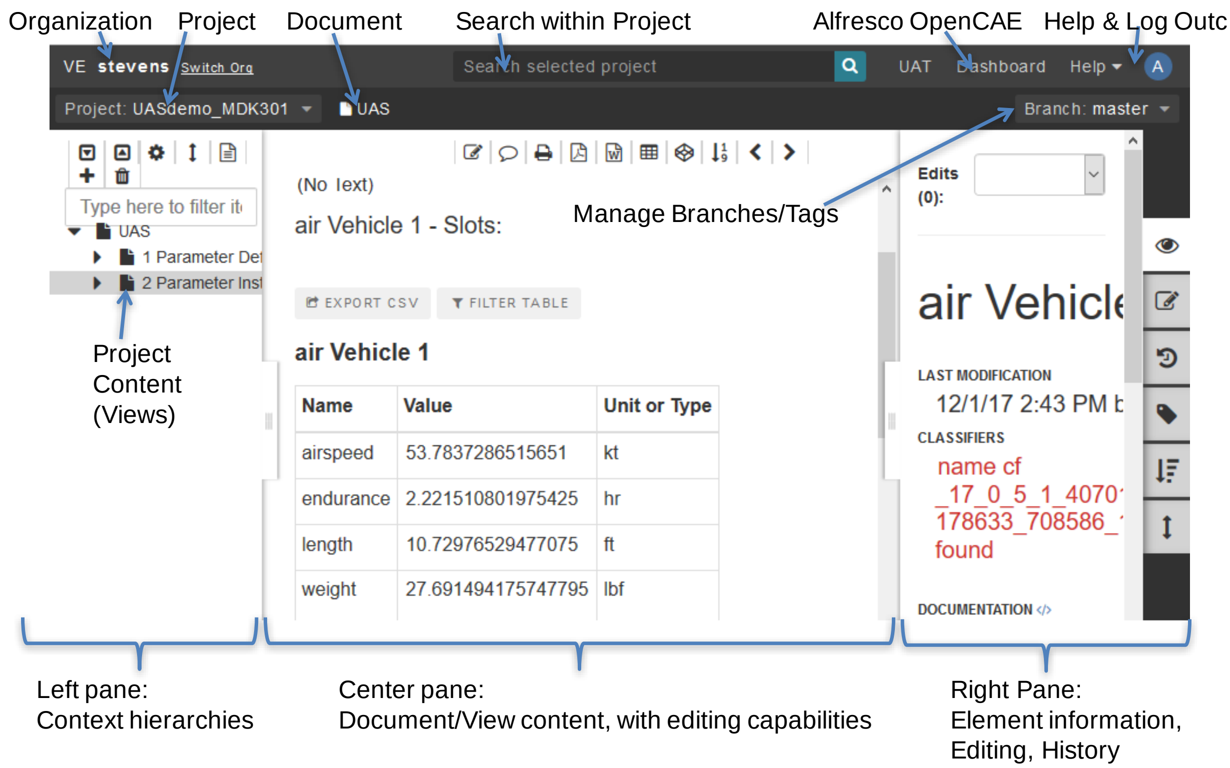

Figure 54. View Editor

6.5 METHODS FOR TRACEABILITY

As discussed in Section 2 and more specifically in Section 2.5, we developed the requirement traceability from the Skyzer System Model to the Skyzer Mission Model inside of the Skyzer System Model using Project Usages as a means to reference those exact requirements between the two models, which is shown in Figure 19.

We use a similar approach to link the Surrogate Contractor refinement of the Skyzer System Model. The Surrogate Contractor models being developed and refined in Element 3 also use Project Usages of the Skyzer System Model. The surrogate contractor provides traceability linkages from the requirements in the Skyzer System Model to the behavior and analyses in the contractor models in a manner similar to that shown in Figure 55. The refined system proposed by Surrogate Contractor was generalized from the Skyzer System Model (IM30). It inherited properties from the System Model, with additional subsystems and properties. For instance, in the Airframe Assembly Subsystem, value properties (e.g., height, length, width) were created by Surrogate Contractor to define the bounding box of the airframe design. There are other traceability matrices for functional requirement and performance requirements, which is shown in Figure 56.

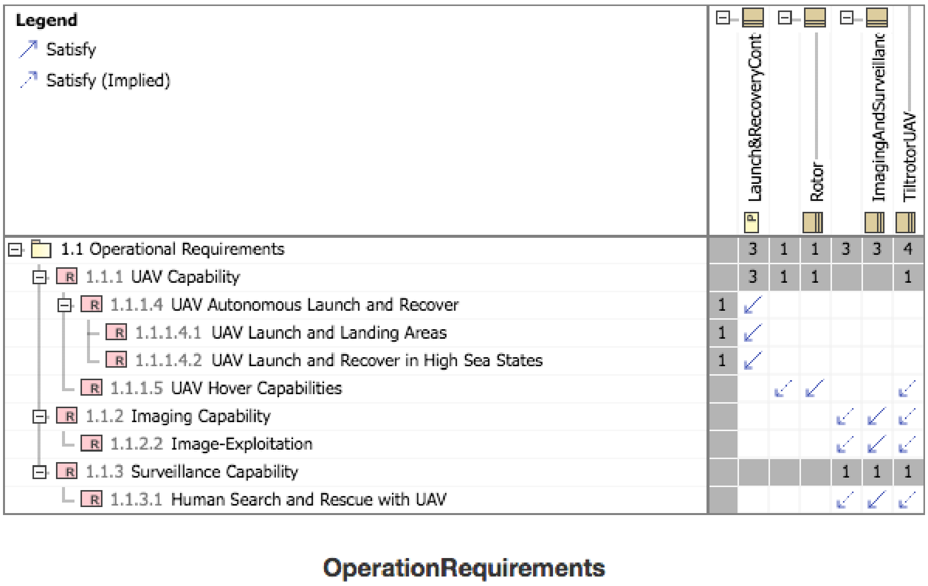

Figure 55. Traceability from Operational Requirements to Requirements in Surrogate Contractor Model

Figure 56 also illustrates how Digital Signoffs are associated with model information such as the Performance Traceability matrix, which relates the Mission Requirements associated with KPPs to design constraints that are analysis supporting evidence that the aircraft design should meet the KPPs. The Source Selection Evaluation Model traces to the specific performance information associated with the surrogate contractor responses, which link to the KPPs.

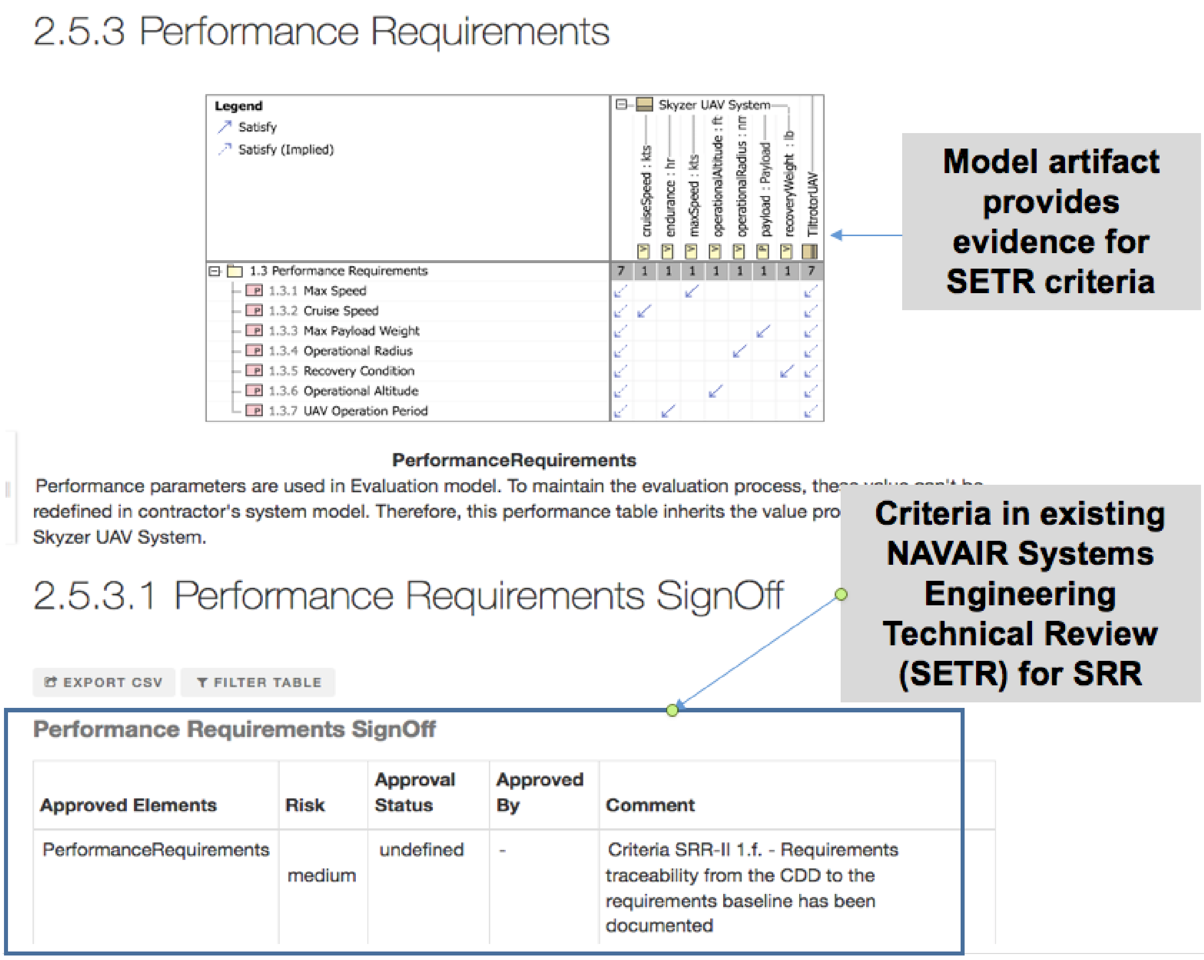

Figure 56. Digital Signoff for SRR-II Criteria in Skyzer RFP View[21]

7 UC04: MODEL-PHYSICS MODELING AND MODEL INTEGRITY

This use case investigates multi-physics modeling, MDAO and model integrity which is also supported by MDAO and approaches for assessing model integrity risks and uncertainty. Model integrity, from our sponsor's perspective, is a means to understand margins and uncertainty in what models and associated simulations "predict" or in other words when/how do we trust the models and associated simulation results. The objectives characterized by the sponsor are to ensure that the research covers the key objectives, which included:

- Include both models to assess "performance" and models for assessing "integrity" such as:
    - Performance: aero, propulsion, sensors, etc.
    - Integrity: Finite Element Analysis (FEA), Computational Fluid Dynamics (CFD), reliability, etc. – can we build it, can we trust it
    - A stated challenge was: how can "integrity" be accomplished when the current situation involves federations of models that are not integrated?

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- Continuous hierarchical and vertical flow enabled by models and iterative refinement through tradespace analysis, concept engineering, and architecture and design analysis

7.1 Surrogate Pilot Design Model Constraint

We have imposed constraints on the mission scenarios, for example as KPPs, for the surrogate pilot to ensure that we have the opportunity to evaluate multi-physic designs and measures for understanding model integrity to support a production readiness decision. During Elements 1 and 2, we used MDAO type analysis such as described in Section 4.4. The more critical aspects that concern our sponsor are the ability to deal with designs in Element 3, that can support a producibility decision associated with Element 4 when multi-physics design elements are involved in the decision process; that is, can we make a production decision from various type of modeling and simulation analyses of a design. An example is shown in Figure 39, which shows that there can be significant differences in the system design tradespace when both CFD and FEA are used in the same MDAO workflow. Therefore, this is another key objective of the surrogate pilot. The objective is to define mission use cases that can be used to force analysis to better understand the feasible multi-physics design options.

7.2 Surrogate Contractor Multi-Physics Design

The surrogate contractor design is not yet complete, but there was a significant amount of design detail that was provided in the RFP response. The generated view from the RFP Response shown in Figure 57 reflects on the refinement of the design using a SysML block definition diagram. Like the mission and system model, the RFP uses the project usage mechanism to link to the requirements from the mission and system models. As shown in Figure 56, the traceability matrix relate the KPP performance requirements from the mission model to the parametric constraints derived from the multi-physics analyses. This particular traceability table provides evidence for the Digital Signoff against “Criteria SRR-II 1.f. - Requirements traceability from the Capability Description Document (CDD) to the requirements baseline has been documented.” Figure 58 shows traceability from the mission requirements to the design constraints. This type of evidence is normally captured as one or more CDRLs and may be required as part of a System Engineering Technical Review. The approach used on the Surrogate Pilot demonstrates how the criteria can be captured as a Digital Signoff and associated with model evidence directly in a model. While those design constraints are captured in the SysML model, they are derived from the multi-physics analysis done in discipline-specific tools. We demonstrated approaches for linking the contractor system model to discipline-specific models such as Computer Aided Engineering (CAE) information, CFD, FEA for tools that do not have direct integrations with the system models. Figure 59 shows a View from the RFP Response model, where the third column of the matrix provide links to a tool and environment, where a subject matter expert could hyperlink into a discipline-specific model analysis to view the details; a CFD analysis is shown in Figure 13.

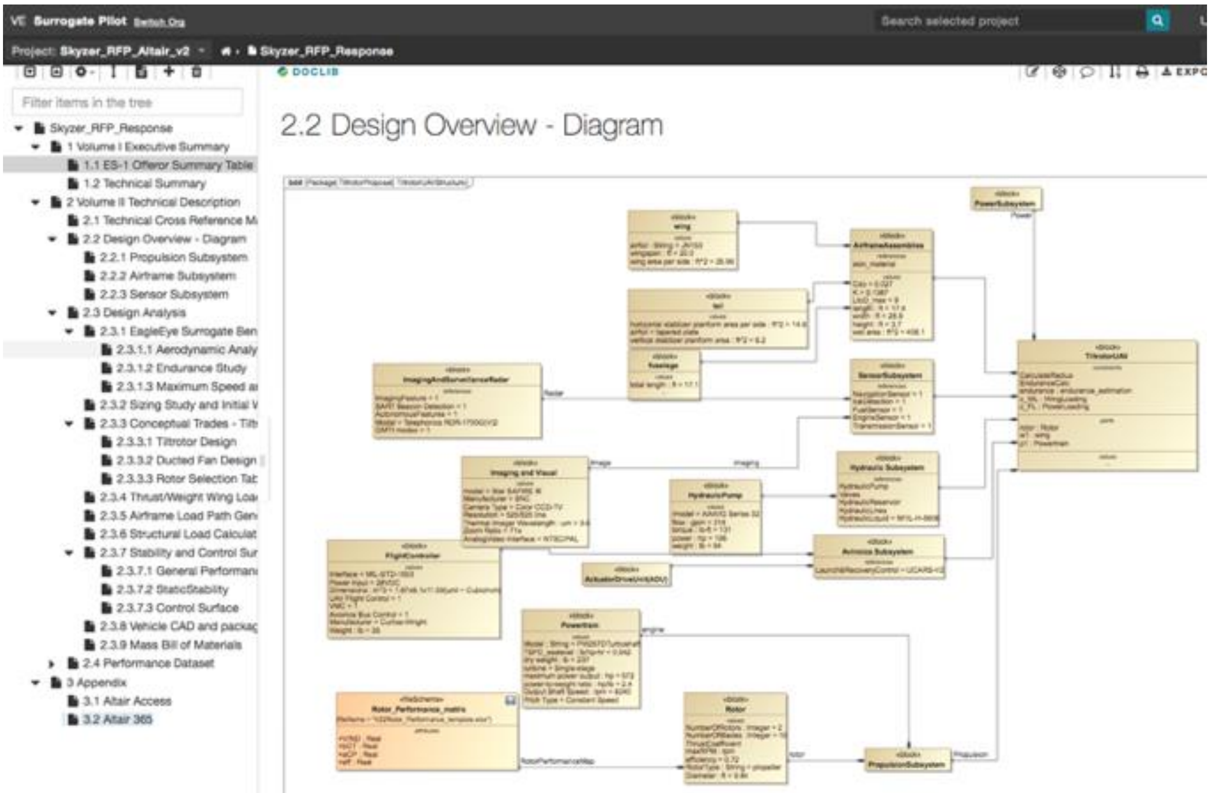

Figure 57. RFP Response Extends and Refines Skyzer System Model provided by Government as GFI[22]

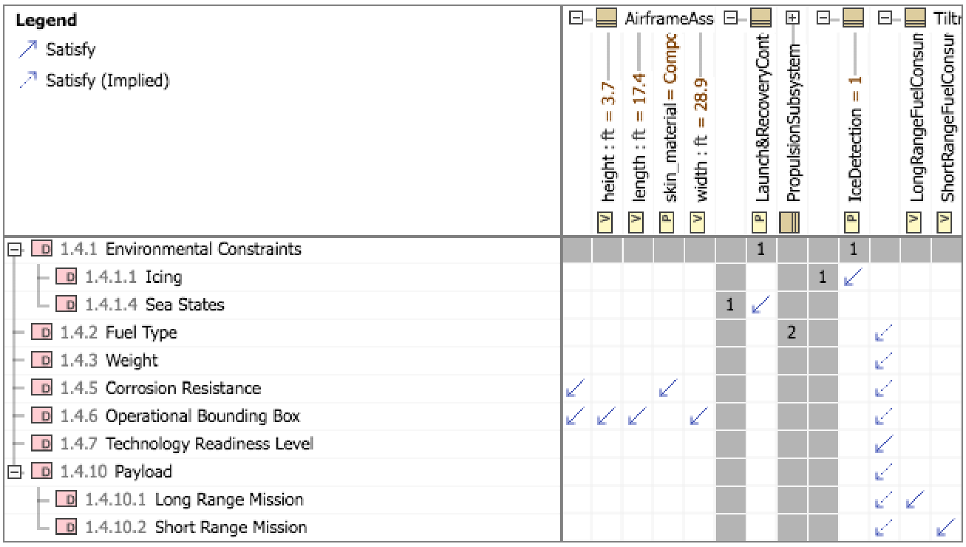

Figure 58. Traceability from Mission Design Constraints to RFP Response Design Constraints[23]

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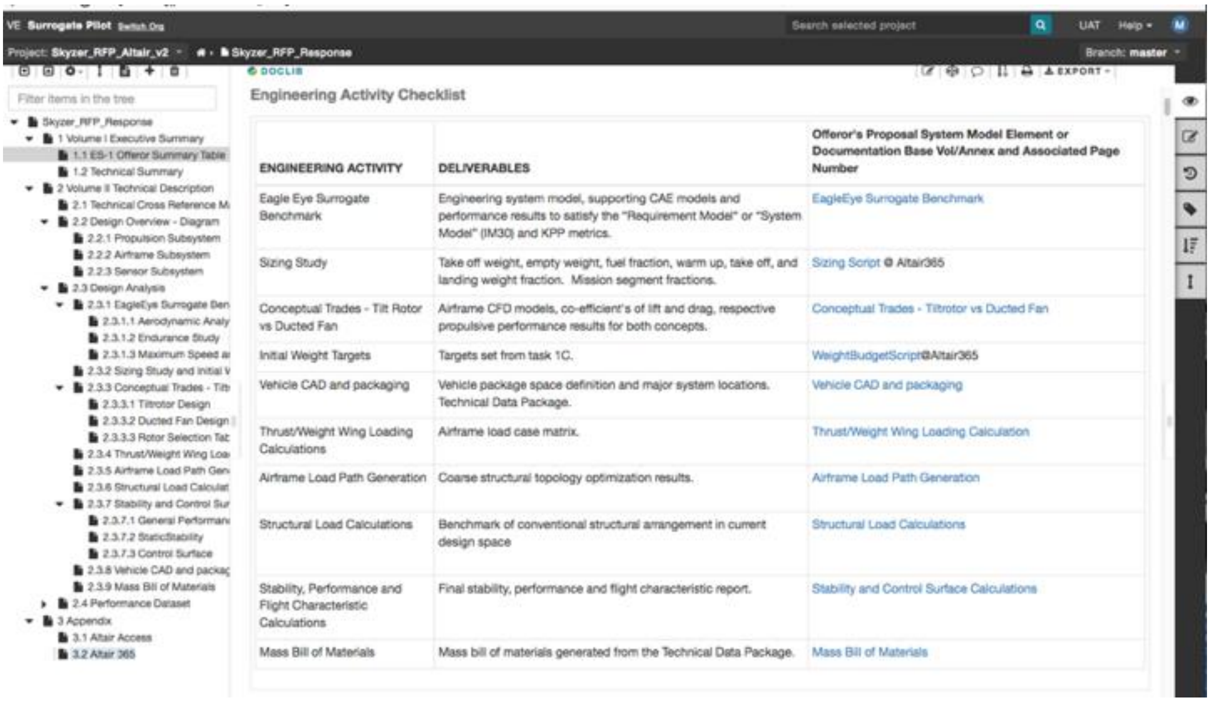

ENGINEERING ACTIVITY	DELIVERABLES	Offeror's Proposal System Model Element or Documentation Base Vol/Annex and Associated Page Number
Eagle Eye Surrogate Benchmark	Engineering system model, supporting CAE models and performance results to satisfy the "Requirement Model" or "System Model" (IM30) and KPP metrics.	EagleEye Surrogate Benchmark
Sizing Study	Take off weight, empty weight, fuel fraction, warm up, take off, and landing weight fraction. Mission segment fractions.	Sizing Script @ Altair365
Conceptual Trades - Tilt Rotor vs Ducted Fan	Airframe CFD models, co-efficient's of lift and drag, respective propulsive performance results for both concepts.	Conceptual Trades - Tiltrotor vs Ducted Fan
Initial Weight Targets	Targets set from task 1C.	WeightBudgetScript@Altair365
Vehicle CAD and packaging	Vehicle package space definition and major system locations. Technical Data Package.	Vehicle CAD and packaging
Thrust/Weight Wing Loading Calculations	Airframe load case matrix.	Thrust/Weight Wing Loading Calculation
Airframe Load Path Generation	Coarse structural topology optimization results.	Airframe Load Path Generation
Structural Load Calculations	Benchmark of conventional structural arrangement in current design space	Structural Load Calculations
Stability, Performance and Flight Characteristic Calculations	Final stability, performance and flight characteristic report.	Stability and Control Surface Calculations
Mass Bill of Materials	Mass bill of materials generated from the Technical Data Package.	Mass Bill of Materials

Figure 59. View of RFP Response Hyperlinks to Discipline-Specific Models Provided in Generated View[24]

As part of the surrogate pilot we are working on the Collaboration Use Case in the AST, linking from Government models on AWS to contractor models. Engineering models supporting the RFP response are viewable through hyperlinks into two Altair virtual collaboration environments (this does require a user account and password).

- Altair 365 for CAD models and mathematics scripts in open-matrix language
- Altair Access for CAE models (e.g. CFD, structural)

There are videos on APAN to illustrate how these environments work. Other analyses completed as part of the RFP response include:

- Performance
- Preliminary Sizing
- Trade of Tilt Rotor vs. Ducted Fan
- Initial Vehicle Weight estimates relative to performance requirements
- Vehicle Packaging considerations
- Demonstrating how using MDAO can support decision making

7.3 Advanced Approaches to Model Integrity

It is currently unclear if NAVAIR, in the context of the SET Framework, will ever deal with multi-physics consideration during Element 1 and 2 of the framework. Most of the analysis will likely be parametric in nature during Element 1 and 2. However, we do know that Sandia National Laboratory has discussed some of the most advanced approaches for supporting uncertainty quantification (UQ) to enable risk-informed decision-making [126]. Their methods and tooling address the subjects of margins, sensitivities, and uncertainties. The

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information they provided reflects on the advanced nature of their efforts and continuous evolution through modeling and simulations capabilities that operate on some of the most powerful high-performance computing (HPC) resources in the world. We heard about their HPC capabilities, methodologies on Quantification of Margins and Uncertainty (QMU), an enabling framework called Design Analysis Kit for Optimization and Terascale Applications (DAKOTA) Toolkit [159], and the need and challenge of Model Validation and Simulation Qualification [156]. They also discussed the movement towards Common Engineering Environment that makes these capabilities pervasively available to their entire engineering team (i.e., the designing system in our terminology). We think their capabilities provide substantial evidence for the types of capabilities that should be part of the risk framework. This section provides additional details.

New approaches and new tools are being made available from SMARTUQ [167], and we should be able to take advantage of these capabilities in the context of the surrogate pilot. SMARTUQ provides modeling capabilities for uncertainty quantification (UQ) and analytics that incorporates real world variability and probabilistic behavior into engineering and systems analyses.

Traditional approaches referred to as Verification, Validation and Accreditation (VV&A) of modeling and simulation capabilities are still relevant and used by organizations. VV&A, in principle, is a process for reducing risk; in that sense VV&A provides a way for establishing whether a particular modeling and simulation and its input data are suitable and credible for a particular use [71]. The words “tool qualification” [72] and “simulation qualification” [156] have also been used by organizations regarding the trust in models and simulations capabilities. A more extension discussion of this subject is provided in RT-141 [33] and RT-157 [26].

8 UC05: Representation to Formalize Monterey Phoenix for Requirement Verification and Validation

This use case investigates the development of SysML representations to formalize the Monterey Phoenix (MP) research under RT-176 to support requirement verification and validation [78]. MCE does provide some unique opportunity to be more effective at contributing V&V evidence in early design. Rigorously defined models can directly support V&V, and this could both subsume cost and risks.

8.1 SysML Representation for Monterey Phoenix

The basic concept is to formalize using SysML graphics, and in this case activity diagrams and then transform into the MP language as shown in Figure 60. MP then uses the formal language to generate graphical representations of the behaviors, as shown in Figure 61 that can be derived from the language of the formalized behavior to a given scope level (e.g., Scope 2 in Figure 60). The verification step does require a person to check the different behavioral representations for correctness. This concept is similar to model checking.

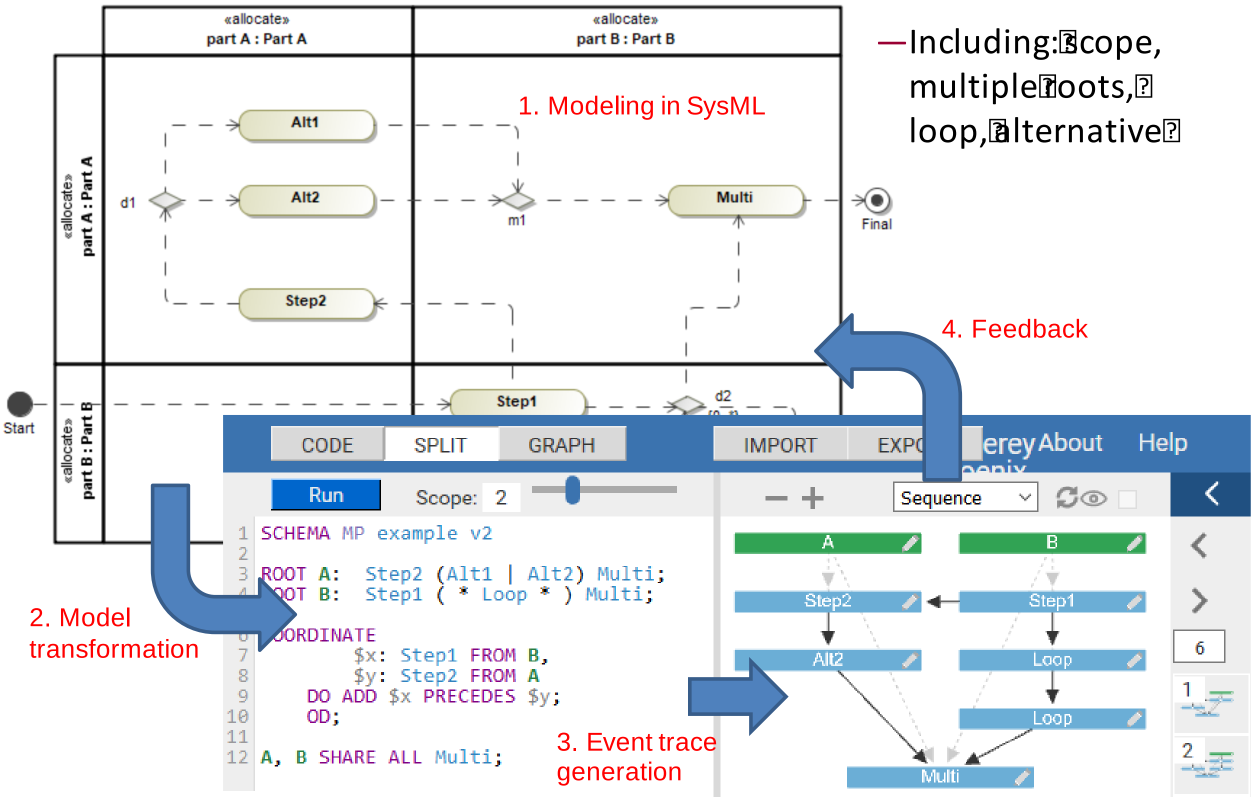

Figure 60. Representation and Transformation from SysML Activity Diagrams to MP

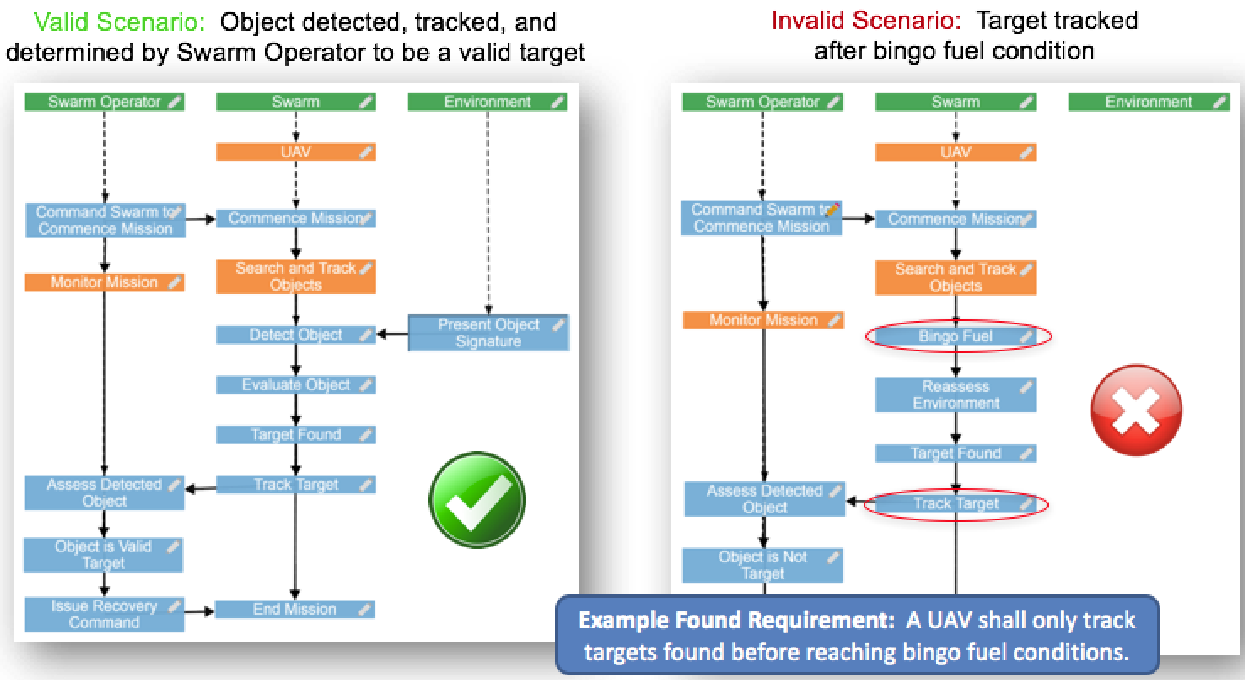

Figure 61. Generated Visualization of Scenarios by Monterey Phoenix

More information on Monterey Phoenix can be found:

- MP Public Website: wiki.nps.edu/display/MP/
- MP Analyzer on Firebird: http://firebird.nps.edu

8.2 Surrogate Pilot Examples Analyzed with Monterey Phoenix

As an initial demonstration of the scenario discussed in Section 8.1 has been applied to an activity diagram from the Skyzer Mission Model. The RT-176 team extracted information from Skyzer Mission Model called the Non-Combat Operations scenario, which is represented as a multi-swim lane activity diagram as shown in Figure 62. We know that the model is difficult to read in the figure, but it can be accessed from APAN. Figure 63 shows one of the generated scenarios produced by MP from this activity diagram. The scenario for the process would be to automatically transform the activity diagram to MP, and then analyze the MP generated scenarios to validate the possible interpretations of the modeled activity diagram behavior.

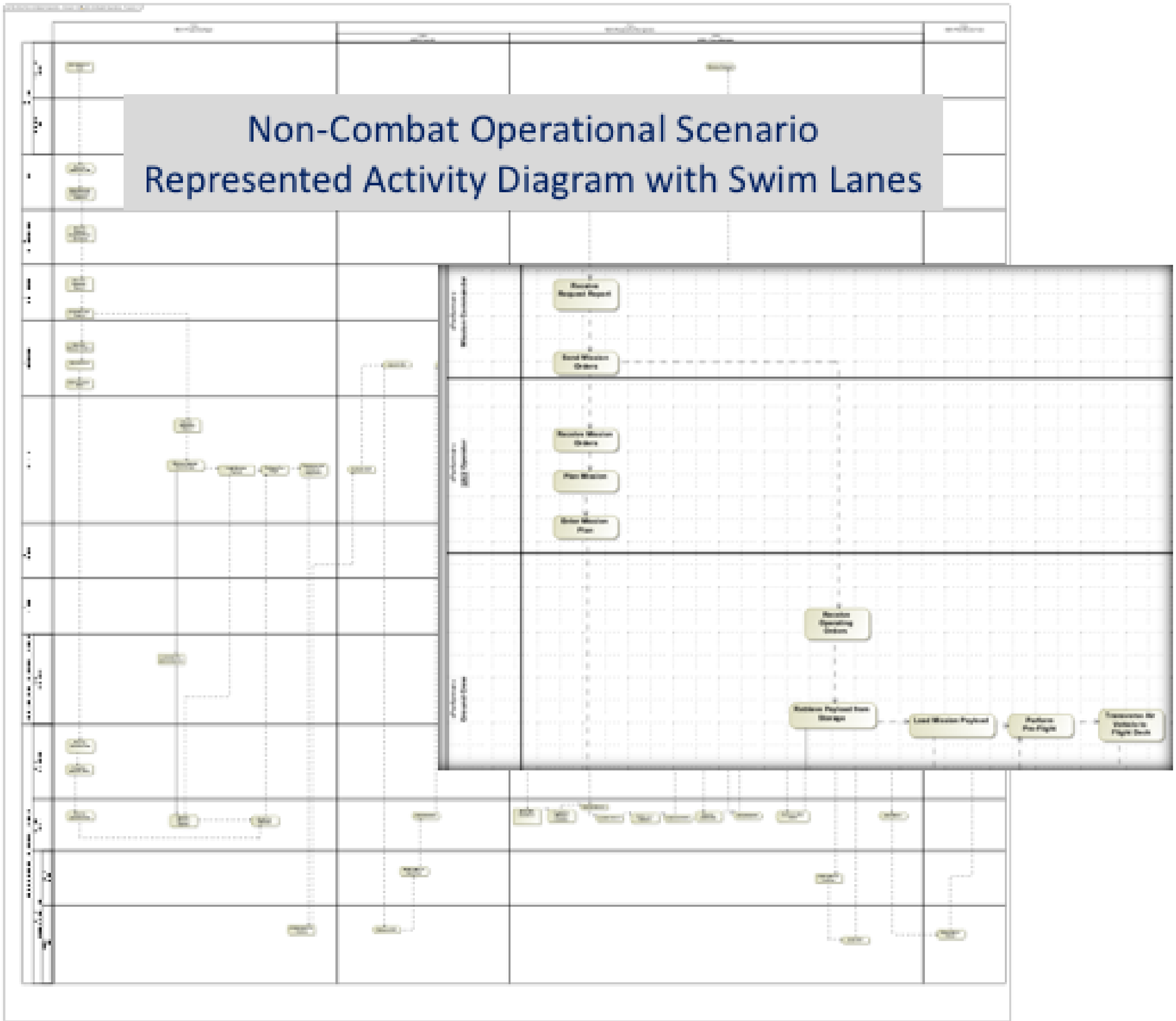

Figure 62. Non-Combat Operational Scenario Represented Activity Diagram with Swim Lanes

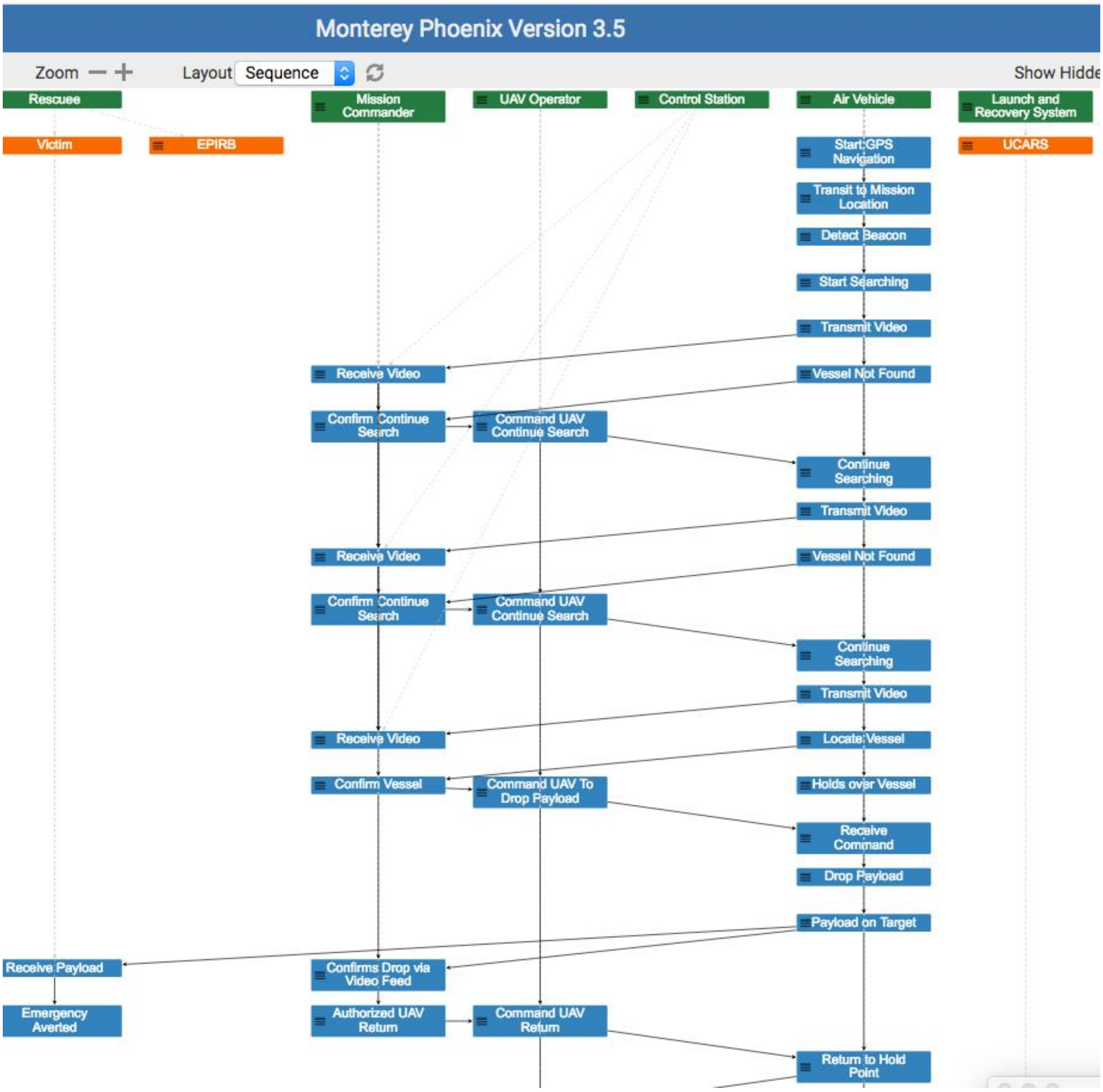

Figure 63. Monterey Phoenix Analysis of Event Generated Scenario

9 UC06: Experimentation and Learning for Research Topics in the Execution of SET

This use case investigates experimentation with the SET Framework concept using the SET surrogate pilot. Much of the information about this use case approach, results and lessons learned is in Part I of this report, or described with additional details throughout this report in the context of the research use cases. Figure 64 shows some of the high-level use cases for the Surrogate Pilot Project. We use DocGen to automatically generate a report from the Surrogate Pilot Project model, which is provided in Appendix A, with some minor formatting. The surrogate pilot contributed initial results to all uses cases shown in Figure 64, except 07 (i.e., Define Dependability Model) and 08 (i.e., Define Logistics Model); we are still interested in these use cases, but did not have the time or resources during Phase 1.

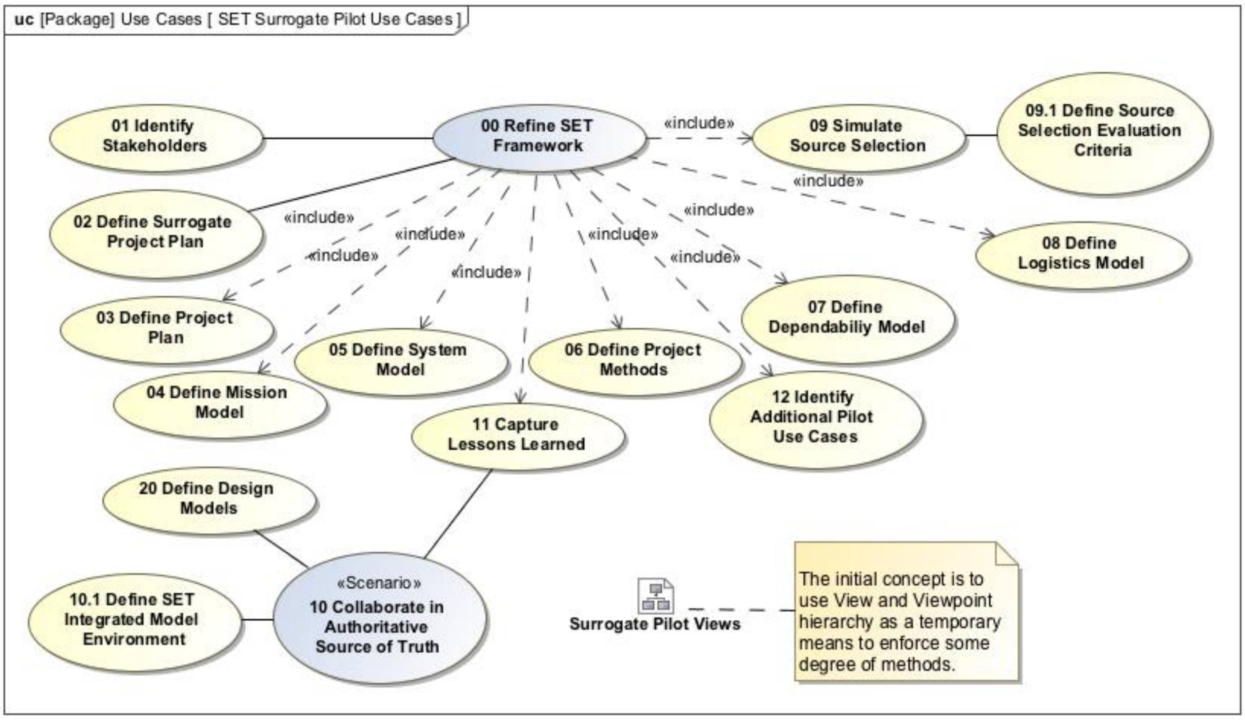

Figure 64. Identify Experimental Objectives for Use Cases

10 UC07: ENTERPRISE TRANSFORMATION TO SUPPORT GOVERNANCE AND WORKFORCE DEVELOPMENT

Enterprises undergoing digital transformation face many challenges related to governance and workforce development. For this use case, the research team conducted a preliminary investigation into potential useful frameworks, strategies and techniques that have resulted from recent research in the area of enterprise transformation. The resulting insights have potential to inform NAVAIR's implementation plans for the continuing transformation.

Transformation research has proven that failure to take a whole enterprise perspective leads to insufficiently evaluated, sub-optimized initiatives to complex enterprise challenges. One useful framework for taking a holistic approach to transformation has emerged from over a decade of research at MIT. Resulting from transformation studies of more than 100 enterprises, the *ARIES Framework*, is applied to generate a holistic blueprint for achieving a desired transformation. The work was motivated by transformation failures, often resulting from going from a transformation need to jump directly to (an incomplete) solution.

What is the ARIES Framework: The ARIES (ARchitecting Innovative Enterprise Strategy) Framework is comprised of: (1) the enterprise element model, specifying ten unique elements for seeing the whole enterprise; (2) the architecting process model having seven activities; and (3) selected techniques and templates. ARIES is grounded in the belief that an enterprise is a complex system, and accordingly must be treated holistically. Enterprise elements make it possible to isolate unique areas of focus, and doing this makes it possible to reduce complexity so that the whole enterprise can be examined. The ten elements emerging from a decade of research are: ecosystem, stakeholders, organization, process, knowledge, infrastructure, information, products and services. Culture, rather than being an element of the enterprise, is viewed as rooted in organization but cross-cutting the ten entangled elements. The ARIES architecting process includes seven activities: (1) understand the enterprise landscape; (2) perform stakeholder analysis; (3) capture current architecture; (4) create a holistic vision of the future; (5) generate alternative architectures; (6) decide on a future architecture; and (7) develop the implementation plan ("blueprint"). Applying the framework results in transformation strategies and initiatives, which are derived using enriched knowledge of the present, attributes of the desired future, and the evaluation of alternatives.

In this phase of the project, the research team has investigated how enterprise transformation research can contribute in two areas of particular importance: (1) enterprise governance in context of SE enterprise deployment; and (2) workforce development.

10.1 Governance and Workforce Development Challenges

Governance is the structure for providing strategic oversight of the transformation effort to achieve results (independent of who the leader might be). It includes ensuring consistent practices, cohesive policies, guidance, processes, and decision making. As stated by Nightingale & Rhodes [127], governance should enable, not create barriers. The transformation governance structure, according to Nightingale & Srinivasan [128] has to "ensure not only the monitoring and control of progress, but also make it possible to reassess strategically the overall direction and constituent projects".

Governance in regard to enterprise transformation necessitates a dual-strategy approach [163]. The first is that the transformation team needs to understand how to fit within current governance structure of the enterprise. Second, there will be a need to establish adjunct and/or independent governance. Governance involves the formal structures and bodies for performing governance activities, as well as the overarching philosophy and supporting policies and enablers.

Research has shown that in establishing governance for sustainment of transformation outcomes, it is very important to take a holistic perspective [127]. The *ARIES Framework Enterprise Element Model is useful* to holistically consider complex enterprises by investigation through various elements (viewpoints/lenses) and relationships of these. The ten elements are shown in Figure 65. Complexity of an enterprise makes it difficult to understand enterprise-level characteristic and behaviors. The benefit of this enabler is that considering transformation using viewpoints enhances the tractability of addressing the myriad aspects of enterprise governance, rather than taking a silo-ed view (e.g., only processes).

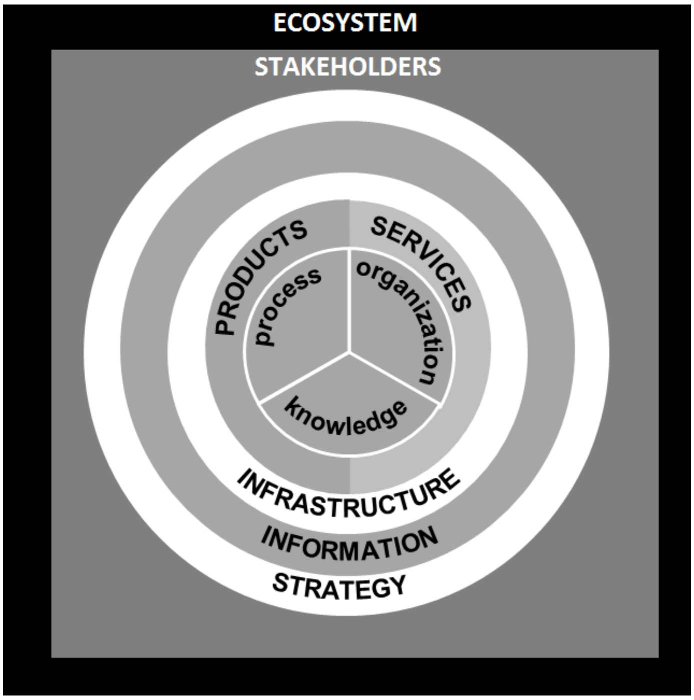

Figure 65. ARIES Framework Ten Enterprise Elements [127]

Table 1 shows examples of questions that may relate to the governance function and activities, when taking the perspective (or viewpoint) of each enterprise element. There are many additional questions to be raised and considered in context of SE transformation governance. These example questions are representative of the questions that might be raised by a transformation team.

Enterprise transformation research has indicated that a team workshop activity with representation from various stakeholder groups can be an effective approach to generate a rich set of questions. These are then used to formulate implementation actions, which can be ordered and prioritized based on team consensus.

Table 1. Holistic Investigation of Governance through Viewpoints

Enterprise Element	Example questions related to governance
Ecosystem	• What external constituents impose constraints and requirements on NAVAIR governance? • What governance models are other enterprises using in context of digital transformation?
Stakeholders	• Who are the various stakeholder groups who will have responsibility and authority for governance activities? • Will any stakeholders have increased or decreased authorities following transformation?
Strategy	• What business models will be used for acquiring and supporting the digital engineering infrastructure? • What strategy will be taken in forming a governance body/function?
Process	• What new processes (e.g., curation) will need to be developed and deployed? • What existing processes will need to be modified and deployed?

Enterprise Element	Example questions related to governance
Organization	• Will any current leadership roles need to be changed and/or created to address governance? • What actions will leadership need to take to sustain transformation outcomes?
Knowledge	• How will digital artifacts be handled from an IP perspective? • How will governance-related lessons learned be captured and shared?
Information	• What existing/new measures will the governance body need to monitor SE Transformation deployment? • What information from other enterprises will be useful for the governance team?
Infrastructure	• What model-based toolsets will be governed at the enterprise level? • Who will be responsible for approving infrastructure decisions (e.g., acquire and retire toolsets)?
Products	• What governance role is needed in the case of digital artifacts being provided as products across organizational units within the enterprise? • How will internal model-based products (e.g., reference models) be controlled?
Services	• What enterprise-level support services (e.g., tool help desk, tool installation) will be provided? • How will the governance body assess cost-effectiveness of providing these services?

Table 2 shows examples of questions that may relate to the workforce development, when taking the perspective (or viewpoint) of each enterprise element. There are many additional questions to be raised and considered in context of SE transformation and workforce. These example questions are representative of the questions that might be raised.

Table 2. Holistic Investigation of Workforce Development through Viewpoints

Enterprise Element	Example questions related to workforce development
Ecosystem	• How are other government enterprises developing their workforce for digital engineering practice? • What external constituents (toolset vendors, universities, training/ consultants) are potential providers for workforce development?
Stakeholders	• Who are the various stakeholder groups who will have responsibility and authority for workforce development activities? • Will any stakeholders have increased or decreased roles and responsibilities following transformation and what will be needed to address this?

Enterprise Element	Example questions related to workforce development
Strategy	• What business models will be used for developing (e.g., training, certification) and/or acquiring (hiring, consulting services) digital engineering competency? • What strategy will be taken to develop the workforce (e.g., organization-wide, program-specific, role specific) and sustain competency over time? • How will workforce development investment be allocated respective to program needs and priorities, enterprise-level needs and priorities, etc.
Process	• How will the workforce be educated on new/modified digital engineering practices? • What will be the approach to develop processes that are tool-neutral?
Organization	• What approach will be used in developing the workforce from an organizational perspective (e.g., organization-wide, program-specific, role specific)? • Will any organizational re-alignment or re-assignments be needed to achieve workforce development objectives?
Knowledge	• What are the knowledge, skills and abilities that are needed in the workforce in the near-term and longer term? • How will the workforce learning on one project be transferred to other future projects?
Information	• What information from other enterprises will be useful to inform workforce development? • How will individuals be informed about opportunities to develop their model-based skills?
Infrastructure	• How will the workforce be informed and educated as digital engineering infrastructure is set up and evolved? • Will individuals need new infrastructure (e.g., desktop computer) to have access to new infrastructure and toolsets?
Products	• What internal products for workforce development (e.g., self-study course, templates, guides) will be available to programs and individuals? • What external products (e.g., INCOSE Competency Framework) are available to support workforce development?
Services	• What enterprise-level skill development support services (e.g., mentoring, communities of practice) will be available? • How will social media technology services (APAN, blogs, etc.) be made available?

10.2 Enterprise Alignment

A governance body performs ongoing oversight to ensure transformation progresses according to plan. Accordingly, there is a need to continuously assess alignment across strategic objectives, stakeholders' value, key processes, and the metrics used to assess the enterprise. The X-Matrix is a construct that has proven to be useful for taking a big-picture view of an enterprise, and finding gaps and misalignment. It is a qualitative tool that shows weak and strong alignment in a visual manner [129][128][127].

The Enterprise Strategic Analysis and Transition (ESAT) Guide describes the Enterprise X-Matrix method, as used to determine the alignment of an enterprise's objectives, metrics, processes, and stakeholder values [129]. The X-Matrix provides a means to concisely visualize the alignment of these aspects of the enterprise by assigning a strong or weak alignment between the different aspects of the enterprise. The upper right quadrant shows how well the enterprise has aligned their strategic objectives with the stakeholder values. The lower right quadrant evaluates the alignment of the enterprise processes with the stakeholder value. The lower left quadrant evaluates the ability of the enterprise's metrics to accurately measure the key processes. And, the upper left quadrant of the X-Matrix shows whether the metrics are accurately evaluating the performance of the enterprise in relationship to the strategic objectives.

Figure 66 shows an example of an X-Matrix for a current state enterprise (a military flight school) resulting from a prior research investigation [73]. The gold-shaded cells present weak alignment and the blue-shaded cells represent strong alignment. While not every empty cell is meant to be filled, the matrix helps to identify gaps and misalignment. For example, the process for "Provision of CSC Simulators" is not measured by any existing metric, and there are no metrics that assess the strategic goal "Enhance Professional Military Education".

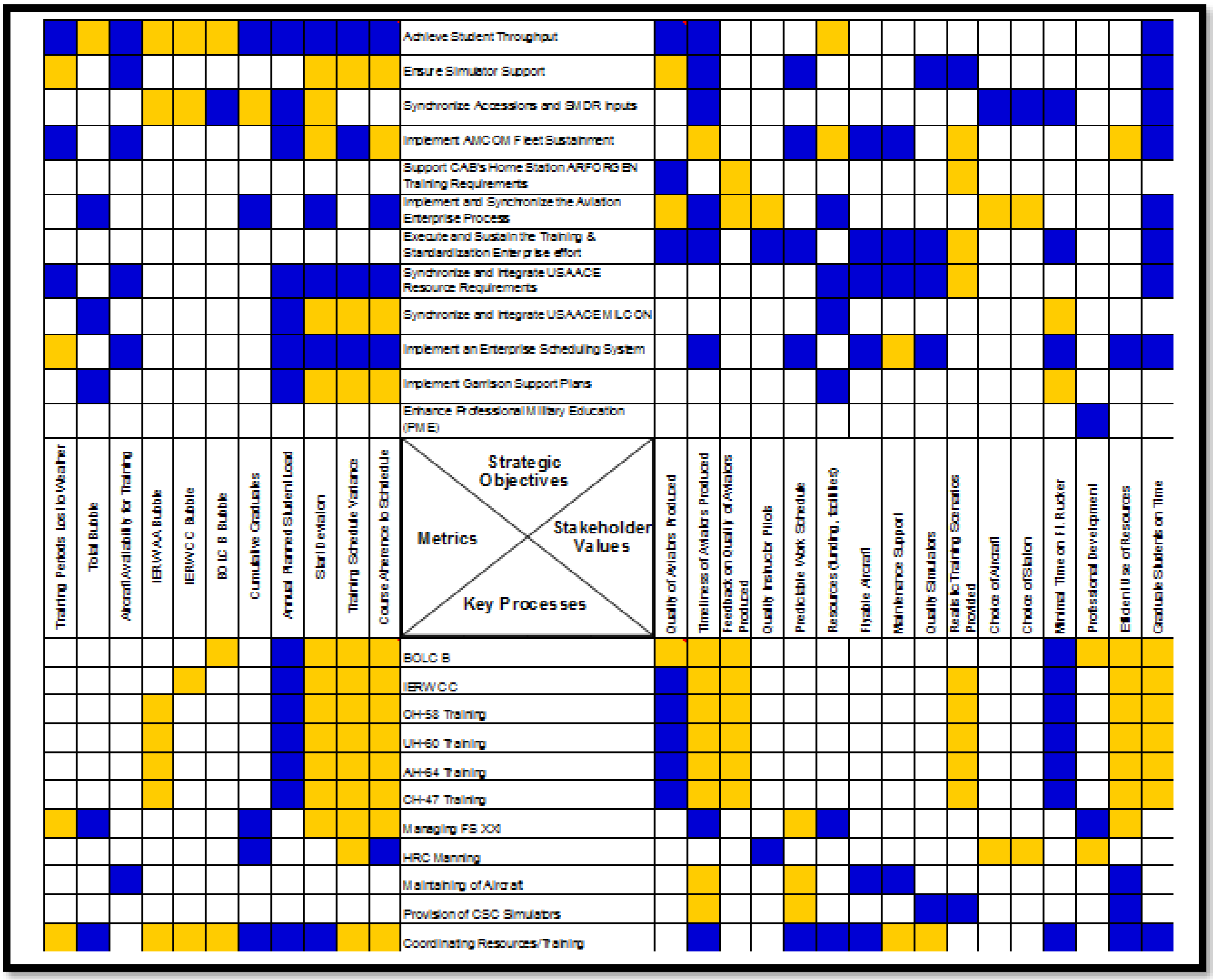

Figure 66. Example X-Matrix of an Enterprise [73]

The X-Matrix can be viewed as a framing technique, and can be customized for the needs of the transformation. The quadrants may vary based on the specific enterprise transformation. Another example of quadrant information used is (1) strategic objectives, (2) stakeholder needs, (3) key initiatives, and (4) metrics (measures). In some transformation programs, specific metrics may not yet be defined so in place of transformation specific metrics, current programs providing measurable information for strategic objectives might be used Song [172].

The X-Matrix offers a potential enabler in the governance team's role in monitoring and assessing transformation over time. The transformation team would produce an X-Matrix of the current enterprise, and use it to identify gaps. A governance body could then update the matrix as transformation progresses, first with planned changes and then as implementation occurs, and use it as a means to judge enterprise alignment. The ongoing monitoring and assessment of enterprise transformation projects engages many different stakeholders, each of whom have individual priorities and limited visibility into the whole enterprise. The power of the X-Matrix is that it offers a shared "boundary object" for ongoing discussion and negotiation (for example, the allocation of limited resources to initiatives). Having a consensus set of metrics specific to transformation provides a common basis for understanding progress.

10.3 Phase 1 Lessons Learned: Implications for Governance and Workforce Development

Section 2.8 summarizes a non-exhaustive list of categorized observations and lessons learned from the Phase 1 effort. Many of these are model technology-specific lessons. While categorization is a useful approach for organization lessons, additional insights may be gained by looking through alternative lenses.

As a means to provide an alternate summary of these from an enterprise (vs. category) perspective, selected lessons learned are mapped to enterprise element viewpoints in Table 3, with possible implications for governance and workforce development. Further formulation of lessons learned with mapping to elements and implications could be performed as part of SET deployment planning.

Table 3 Selected SE Transformation Lessons Learned Mapped to Enterprise Elements

SET Lessons Learned Category	Enterprise Element	Implications for Governance	Implications for Workforce Development
Objectives Identification for Phases	Strategy	Standard use of NASA/JPL ontology	Objectives identified to cut across mission, system, RFP, and source selection processes providing unclassified modeling examples for workforce training
infrastructures for IME tools and AST	Infrastructure	Standardize guidance and schedules for infrastructure for new programs	Inform and train new program workforce on infrastructure at start of program
Interactive interaction with surrogate contractor during RFI and pre-RFP very useful	Strategy	Need to establish policy for early collaboration using models concerning information sharing	Need to train workforce on interaction policies and process for doing so
Technically feasible to develop everything in a model	Strategy	Promote culture to embrace the broad use models where valuable. Encourage consideration and justification for model use/no use decision	Open MBEE and associated modeling tools provided key capabilities, and provided underlying infrastructure for implementation of AST
Methods and guidance	Knowledge	Standard modeling guidelines	Train workforce on standard methods and how to tailor if needed

SET Lessons Learned Category	Enterprise Element	Implications for Governance	Implications for Workforce Development
Model Management	Process	Ensure comprehensive development/ application of model management practices, as distinct but aligned with CM	Provides example for doing modeling management in the context of AST that goes beyond traditional CM of documents
Model Management	Organization		Promote involvement in community efforts to standardize model management practice
Model Modularization	Strategy	Promote modularization as strategy to promote reuse, isolate classified information, provide access control, reduce complexity, etc.	Strategic decision to educate workforce on model modularization practice, and use of toolsets
Project Usages for Model Modularization	Infrastructure	Ensure modeling toolset capabilities leveraged to achieve benefits of modularity	Provides means for working on separate aspects of lifecycle in parallel such a mission and system model that are also linked
RFI and RFP	Process	Guidance for model-based RFI and RFP process	Educate workforce on RFI and RFP processes in model-based situation
Access to AST	Information	Investigate feasibility of providing access to public domain hosted server information	Provides exemplar to inform workforce how to work collaboratively on models that span the lifecycle
Team SME with modelers	Organization	Promote a culture of collaboration and open communications between modelers and SME	Organize training with teamed SMEs and modelers to reinforce use of approach

11 SERC RESEARCH SYNERGIES

This section summarizes some synergies to the ongoing NAVAIR research tasks that are briefly mentioned in this report to inform readers of the relationships to these other activities.

11.1 RT-168 ARDEC Research

The most significant research synergies are coming from the ARDEC research under RT-168. We do many types of event, meetings, demonstrations and discussions with ARDEC that include NAVAIR. We use a Model Based System Engineering (MBSE) approach to model aspects of our project. We elaborate the research tasks using high-level use cases, relating those use cases, and associating the use cases with stakeholders involved in the research as shown in Figure 67. It should be clear that the use cases are related, and stakeholders (including some from ARDEC) are involved in multiple use cases. For example, both ARDEC and NAVAIR use OpenMBEE, Docker, MDAO, and have broad interests in ontologies and SWT.

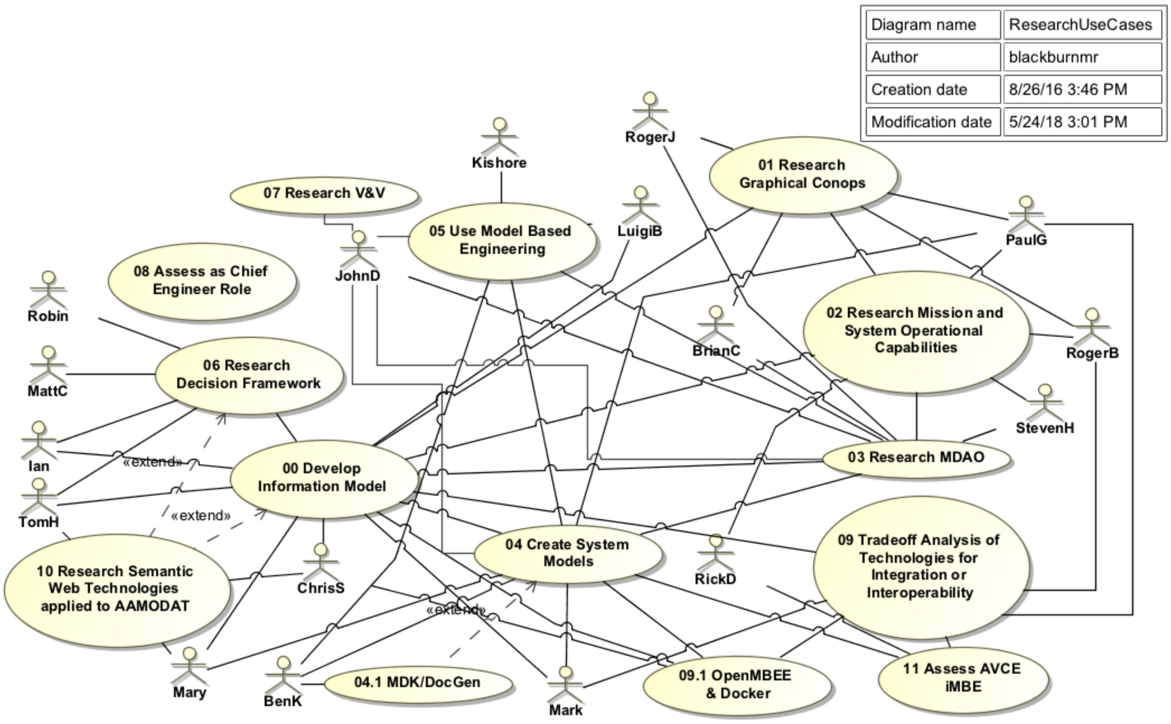

Figure 67. High-level Research Use Cases

11.2 RT-176 Verification and Validation (V&V) of System Behavior Specifications

Our NAVAIR sponsor had requested that the SERC RT-176 research task being led by Dr. Kristin Giammarco, which is discussed in Section 8. The Monterey Phoenix capability is being applied to the Skyzer Mission Model.

11.3 OpenMBEE and Open Collaboration Group for MBSE

We are members of the OpenMBEE Collaboration Group for MBSE leadership team and committers team. We use OpenMBEE in our lab and on the surrogate pilot, and contribute to the community effort (e.g., created Docker) in order to advance its capabilities. We often present our efforts at the OpenMBEE Collaboration Group bi-weekly meetings.

11.4 Semantic Technologies Foundation Initiative for Systems Engineering

The NASA/JPL Symposium and Workshop on MBSE had a keynote talk given by Steve Jenkins that was fundamentally based on SWT and a foundational ontology for Systems Engineering developed my NASA/JPL in January of 2017. There were also two breakout sessions on the subject SWT. There was significant attendance at the break out session titled: "Ontologies, Formalisms, & Reasoning" possibly due to the motivation given by Steve Jenkins. In general, there is progress being made in this area and there is significant interest. Dinesh Verma has initiated an effort with the support of Chi Lin, Steve Jenkins and Mark Blackburn to bring a community of people together in an attempt to create and ecosystem on Semantic Technologies for Systems Engineering.

The working group has created a charter and mission:

- Charter
  - The Semantic Technologies Foundation Initiative for Systems Engineering is to promote and champion the development and utilization of ontologies and semantic technologies to support system engineering practice, education, and research.
- Mission
  - The mission of the initiative is to collect a suite of interoperable ontologies that are logically well-formed and accurate from both scientific and engineering points of view. The initiative will charter a collective of stakeholders that are committed to collaboration and adherence to shared semantic principles for the advancement of systems engineering. To achieve this, initiative working group participants will voluntarily adhere to and contribute to the development of an evolving set of principles including open use, collaborative development, and non-overlapping and appropriately-scoped content. They will capture and maintain metadata for each ontology to encourage implementation and reuse.

11.5 National Defense Industry Association Modeling and Simulation

National Defense Industry Association (NDIA) Modeling and Simulation group is looking at approaches for using digital engineering for competitive down select. We have been involved in all of these efforts to further the objectives of our sponsor since August of 2016 and present periodically at different sessions as recent as March 2019. These events help inform industry about the efforts of the NAVAIR SE Transformation in the context of Surrogate Pilot experiments [23] [41] [108].

At the request of David Allsop from Boeing, we also connected a few people from our NAVAIR visits to discuss the issue of deriving MDAO parametrics from high-fidelity models, or more generally having some type of bi-directionality between parametric models and higher fidelity simulations (which can "break" the parametric chains). Dr. Dave McCormick who runs the MDAO lab for Northrop Grumman gave a relevant presentation at the April National Defense Industrial Association (NDIA) Modeling and Simulation bi-monthly committee meeting on some of challenges, which we believe are relevant to future research, such as:

- Rapid re-parameterization of completely new concepts
- Ability to incorporate static models

- Ability to bring in static changes “underneath” the parameterization
- Ability to incrementally add to parameterization
- Ability to rapidly alter the sizing logic behind models

11.6 Aerospace Industry Association CONOPS for MBSE Collaboration

This is a follow-up to the effort completed last year which developed a white paper on the Life Cycle Benefits of Collaborative MBSE Use for Early Requirements Development [3]. This white paper discusses the current state and benefits of MBSE across the entire life cycle and provides proposals for addressing such issues as MBSE Collaborative Framework, Government Data Rights, Intellectual Property, and Life Cycle Effectiveness with MBSE.

The effort for this year involves many of the industry contractors to NAVAIR and DoD. The results should produce a white paper describing a CONOPS for how industry and government can collaborate through MBSE.

12 Part II Summary

Our research is demonstrating the art-of-the-possible in using MCE methods and Integrated Modeling Environment (IME) technologies in the context of Surrogate Pilot experiments. The pilot is developing an experimental UAV system called Skyzer, and Phase 1 completed a deep dive on search and rescue mission operational scenarios. We created an Authoritative Source of Truth (AST) concept for the government-side and contractor side of the surrogate pilot project. We have been successful at the initial use and deployment of OpenMBEE as a core element in the experimental IME for an AST. While modeling everything may not be practical for all projects, the surrogate pilot team has demonstrated the feasibility of using modeling methods at the mission, systems, and even using models for the request for proposal, statement of work, and source selection using models. We have used DocGen to demonstrate how to generate stakeholder-relevant views from the various models.

We demonstrated a new operational paradigm between government and industry in the execution the SET Framework in the context of an AST. We are sharing detailed aspects of the surrogate pilot experiments discussed in this report on the All Partners Network (APAN) in order to journal our project, socialize these new operational concepts, and to solicit feedback from industry, government and academia.

We are participating with the three Navy systems commands (SYSCOM) NAVAIR, NAVSEA and SPAWAR on an initiative to scope an effort to build Navy and DoD interoperable ontologies. This effort is also jointly led by our RT-195 team and NAVAIR sponsors. There are cross SYSCOM working sessions conducted for this effort, which has been opened to other government organizations. As part of the NAVAIR SE Transformation effort, a Suite of NAVAIR Acquisition System Reference Models (ASRMs) are under development in which we are participating by leveraging our connections with industry to get subject matter experts from industry to be involved in the review process. We too are part of the review team, and plan to align our surrogate pilot models with the ASRM approach.

As we move to the next phase of this research task we will circle back to Phase 2 of the SET Framework assessment and focus on other uses cases such as: alignment with ASRM and the

NAVAIR Systems Engineering Method (NAVSEM), Model Management Guidelines, Airworthiness deep-dive, new forms of contracting and review in an AST, Capability-Based Test and Evaluation (CBT&E), Digital Signoffs and possibly cyber security. Additional use case candidates delayed from start of Phase 2 due to limited resources include: Scenarios for Alternative Analysis prior to "Milestone A," Mission Systems, Logistics, Dependability and Creating a Project Management Model.

We have created two perspectives on roadmaps, one for technologies that are likely to enable DE, and a second perspective is for a roadmap based on the DoD Digital Engineering Strategy goals reflected in the context of an evolution of Mission and Systems Engineering. A key reflection is that these roadmaps anticipate the increased need to formalize the underlying information model as we move to the right (i.e., future), which can exploit more computational automation such as (i.e., AI, machine learning, etc.), enabled by high performance computing.

Finally, we will continue to foster our synergies with other research tasks with the US Army ARDEC, Semantic Technologies for System Engineering Initiative, Digital Engineering Working Group, NDIA, Aerospace Industry Association, INCOSE MBX Ecosystem, and the OpenMBEE Collaboration Group for MBSE.

13 ACRONYMS AND ABBREVIATION

This section provides a list of some of the terms used throughout the paper. The model lexicon should have all of these terms and many others.

2D	Two dimensions
3D	Three dimensions
AADL	Architecture Analysis & Design Language
ACAT	Acquisition Category
ACES	Automated Concurrent Engineering System
AFD	Assessment Flow Diagram
AFT	Architecture Framework Tool of NASA/JPL
AGI	Analytical Graphics, Inc.
AGM	Acquisition Guidance Model
AGS	Army Game Studio
ALM	Application Lifecycle Management
AMMODAT	Armament Analytics Multiple Objective Decision Analysis
ANSI	American National Standards Institute
AP233	Application Protocol 233
APAN	All Partners Network
API	Application Programming Interface
AR	Augmented Reality
ARDEC	Armament Research, Development and Engineering Center
ASELCM	Agile Systems Engineering Life Cycle Model
ASR	Alternative System Review
AST	Authoritative Source of Truth
ATL	ATLAS Transformation Language
AVCE	Armament Virtual Collaboratory Environment
AVSI	Aerospace Vehicle Systems Institute
BDD	SysML Block Definition Diagram
BN	Bayesian Network
BNF	Backus Naur Form
BOM	Bill of Material
BPML	Business Process Modeling Language
C-BML	Coalition Battle Management Language
CAD	Computer-Aided Design
CASE	Computer-Aided Software Engineering
CDR	Critical Design Review
CEO	Chief Executive Officer
CESUN	International Engineering Systems Symposium
CFD	Computational Fluid Dynamic
CGF	Computer Generated Forces
CMM	Capability Maturity Model
CMMI	Capability Maturity Model Integration
CONOPS	Concept of Operations
CORBA	Common Object Requesting Broker Architecture
COTS	Commercial Off The Shelf
CPS	Cyber Physical System
CREATE	Computational Research and Engineering for Acquisition Tools and Environments
cUAS	Counter UAS
CWM	Common Warehouse Metamodel
DAA	Data Acquisition and Aggregation layer

DASD	Deputy Assistant Secretary of Defense
dB	Decibel
DBMS	Database Management System
DAG	Defense Acquisition Guidebook
DARPA	Defense Advanced Research Project Agency
DAU	Defense Acquisition University
DCDR	Digital design from Critical Design Review (CDR)
DE	Digital Engineering
DIS	Distributed Interactive Simulation
DISA	Defense Information Services Agency
DL	Descriptive Logic
DLR	DLR Institute of Flight
DoD	Department of Defense
DoDAF	Department of Defense Architectural Framework
DoE	Design of Experiments
DOORS	Requirement Management product
DOORS-NG	DOORS-Next Generation
DSEEP	Distributed Simulation Engineering and Execution Process
DSL	Domain Specific Languages
DSM	Domain Specific Modeling
DSM	Design Structure Matrix
DSML	Domain Specific Modeling Language
E/DRAP	Engineering Data Requirements Agreement Plan
ERP	Enterprise Resource Planning
ESP:HE	ESP: Higher Echelon
ERS	Engineered Resilient Systems
ESP	Early Synthetic Prototype
FAA	Federal Aviation Administration
FEA	Finite Element Analysis
FMEA	Failure Modes and Effects Analysis
FMI	Functional Mockup Interface
FMU	Functional Mockup Unit
FOM	Federation Object Model
GAO	Government Accounting Office
GFI	Government Furnished Information
GUI	Graphical User Interface
HLA	High Level Architecture
HPC	High Performance Computing
HPCM	High Performance Computing Modernization
HW	Hardware
I&I	Integration and Interoperability
IBM	International Business Machines
IBD	Internal Block Diagram (SysML)
ICD	Interface Control Document
ICT	Institute for Creative Technologies
ICTB	Integrated Capability Technical Baseline
IDEF0	Icam DEFinition for Function Modeling
IEEE	Institute of Electrical and Electronics Engineers
IME	Integrated Modeling Environment
iMBE	AVCE-Integrated Model-Based Engineering
INCOSE	International Council on Systems Engineering
IPR	Integration Problem Report

IoIF	Interoperability and Integration Frameowk, previously referred to as Integration and Interoperability Framework
IRL	Integration Readiness Level
ISEDM	Integrated Systems Engineering Decision Management
ISEF	Integrated System Engineering Framework developed by Army's TARDEC
ISO	International Organization for Standardization
IT	Information Technology
IWC	Integrated Warfighter Capability
JCIDS	Joint Capabilities Integration and Development System
JEO	Jupiter Europa Orbiter project at NASA/JPL
JSF	Joint Strike Fighter
JPL	Jet Propulsion Laboratory (NASA)
JSON	JavaScript Object Notation
KPP	Key Performance Parameter
KSA	Key System Attributes
LIDAR	Light Detection and Ranging
LOC	Lines of Code
LSL	Lab Streaming Layer
M&S	Modeling and Simulation
MARTE	Modeling and Analysis of Real Time Embedded systems
MATRIXx	Product family for model-based control system design produced by National Instruments; Similar to Simulink
MBE	Model Based Engineering
MBEE	Model Based Engineering Environment
MBSE	Model Based System Engineering
MBT	Model Based Testing
MC/DC	Modified Condition/Decision
MCE	Model Centric engineering
MDA®	Model Driven Architecture®
MDAO	Multidisciplinary Design, Analysis and Optimization
MDD™	Model Driven Development
MDE	Model Driven Engineering
MDK	Model Development Kit – OpenMBEE plugin to MagicDraw
MDSD	Model Driven Software Development
MDSE	Model Driven Software Engineering
MIC	Model Integrated Computing
MMM	Modeling Maturity Model
MMS	Model Management System (part of OpenMBEE)
MoDAF	Ministry of Defence Architectural Framework (United Kingdom)
MOE	Measure of Effectiveness
MOF	Meta Object Facility
MOP	Measure of Performance
MP	Monterey Phoenix
MRL	Mixed Reality Lab
MxRP	Mixed Reality Prototyping
MSDL	Military Scenario Definition Language
MVS	Multiple Virtual Storage
N2	N-squared diagram
NASA	National Aeronautics and Space Administration
NASA/JPL	NASA Jet Propulsion Laboratory
NAVAIR	U.S. Navy Naval Air Systems Command
NAVSEA	U.S. Naval Sea Systems Command
NDA	Non-disclosure Agreement

NDIA	National Defense Industrial Association
NEAR	Naval Enterprise Architecture Repository
NPS	Naval Postgraduate School
NSGA	Non-dominated Sorting Genetic Algorithm
OCL	Object Constraint Language
OMG	Object Management Group
OO	Object oriented
OpenMBEE	Open Model Based Engineering Environment
OpenVSP	Open Vehicle Sketch Pad
OSD	Office of the Secretary of Defense
OSLC	Open Services for Lifecycle Collaboration
OV1	Operational View 1 – type of DoDAF diagram
OWL	Web Ontology Language
PAR	Parametric Block in SysML
PDM	Product Data Management
PDR	Preliminary Design Review
PEA	Post Exercise Analysis
PES	Physical Exchange Specification
PIA	Proprietary Information Agreement
PIM	Platform Independent Model
PLM	Product Lifecycle Management
POR	Program of Record
PRR	Production Readiness Review
PSM	Platform Specific Model
QMU	Quantification of Margins and Uncertainty
RDEC	US Army Research Development and Engineering Center
RDF	Resource Description Framework
RDECOM	US Army Research, Development and Engineering Command
RT	Research Task
RTI	Runtime Infrastructure
RFI	Request for Information
RFP	Request for Proposal
RPM	Revolutions Per Minute
RPR FOM	Real-time Platform Reference Federation Object Model
ROI	Return On Investment
SAVI	System Architecture Virtual Integration
SE	System Engineering
SERC	Systems Engineering Research Center
SETR	System Engineering Technical Review
Simulink/Stateflow	Product family for model-based control system produced by The Mathworks
SCR	Software Cost Reduction
SDD	Software Design Document
SE	System Engineering
SET	Systems Engineering Transformation
SFR	System Functional Review
SISO	Simulation Interoperability Standards Organization
SLOC	Software Lines of Code
SME	Subject Matter Expert
SOAP	A protocol for exchanging XML-based messages – originally stood for Simple Object Access Protocol
SoS	System of Systems
Software Factory	Term used by Microsoft
SPARQL	SPARQL Protocol and RDF Query Language

SRR	System Requirements Review
SRS	Software Requirement Specification
SST	Single Source of Truth
SSTT	Single Source of Technical Truth
ST4SE	Semantic Technologies for Systems Engineering
STOVL	Short takeoff and vertical landing
SVR	System Verification Review
SW	Software
SWT	Semantic Web Technology
SysML	System Modeling Language
TARDEC	US Army Tank Automotive Research
TBD	To Be Determined
TRL	Technology Readiness Level
TRR	Test Readiness Review
Turtle	Terse RDF Triple Language
UAV	Unmanned Aerial Vehicle
UAS	Unmanned Aerial System
UC	Use Case
UCAV	Unmanned Combat Air Vehicles
UML	Unified Modeling Language
Unix	An operating system with trademark held by the Open Group
UQ	Uncertainty Quantification
US	United States
USD	US Dollars
USC	University of Southern California
VHDL	Verilog Hardware Description Language
VR	Virtual Reality
V&V	Verification and Validation
XMI	XML Metadata Interchange
XML	eXtensible Markup Language
XSLT	eXtensible Stylesheet Language family (XSL) Transformation
xUML	Executable UML

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PART III: APPENDICES OF RESEARCH DETAILS

Appendix A was automatically generated from the Surrogate Pilot Project model using DocGen. The only elements that were modified were to apply the Heading styles and caption styles to the figures and tables, and some minor formatting. Appendix B provides summary of research provided by University of Maryland. Appendix C provides a summary from an article submitted to INCOSE Insight on the approach used to formalize the Decision Framework concept using SysML, MBSEPak, and ModelCenter.

A. NAVAIR - SERC SYSTEMS ENGINEERING TRANSFORMATION SURROGATE PILOT: SE TRANSFORMATION SURROGATE PILOT PROJECT

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A.1 Chapter 1. Surrogate Pilot Overview

The new operational paradigm starts with mission engineering, analysis and acquisition led by government (Elements 1 & 2), and a collaborative design effort led by industry (Elements 3 & 4). Briefly the concept of the new SET framework for transforming from a document-centric process with monolithic reviews to an event-driven model-centric approach involves, but is not limited to:

- A concept for collaborative involvement between Government and Industry to assess mission and System of Systems (SoS) capability analyses, where NAVAIR has the lead
- Involve industry in SoS capabilities assessments during mission-level analysis (to the degree possible)
- Iteratively perform tradespace analyses of the mission capabilities using approaches such as Multidisciplinary Design, Analysis and Optimization (MDAO) as a means to develop and verify a model-based specification
- Synthesize an engineering concept system model characterized as a model-centric specification and associated contractual mechanism based on models or associated formalism
- At the contractual boundaries, industry will lead a process to satisfy the conceptual model addressing the Key Performance Parameters (KPPs), with particular focus on Performance, Availability, Affordability, and Airworthiness to create an Initial Balanced Design
- Industry too applies MDAO at the system and subsystem level
- There is a potential need to iterate back to re-balance the needs if the tradespace analyses of the solution/system for the program of record (POR) cannot achieve mission-level objectives
- All requirements are tradeable if they don’t add value to the mission-level KPPs
- There are asynchronous activities in creating an Initial Balanced Design Government and Industry must work together to assess “digital evidence” and “production feasibility”

This is a work in progress. This document was completely generated from a combination of models as described in this document.

The purpose of this project is to simulate the ***Execution*** of the new Systems Engineering Transformation (SET) Framework using a "completely" model-centric approach. Therefore, while modeling everything may not be practical for all projects, the plan is to attempt to use models exclusively in order to demonstrate the feasibility and desired approaches that will be captured in reference models. The current model defines the first phase of the Surrogate Pilot.

Mission: Collaboration between Government and Industry in Model-based Acquisition under SET Framework

Goal: Execute SET Framework to Assess, Refine, and Understand a New Paradigm for Collaboration in Authoritative Source of Truth (AST)

Objectives (non exhaustive - see Surrogate Pilot Objectives):

- Formalize experiment to answer questions about executing SET framework using Surrogate Contractor (SC)
- ”Government team” creates mission, system (& other) models, “generates specification/RFP,” & provides acquisition models to SC as Government Furnished Information (GFI)
- SC refines GFI reflects corrections/innovations with physical allocation views with multi-physics- based Initial Balanced Design
- Simulate continuous virtual reviews and derive new objective measures for assessing maturing design in AST
- Demonstrate visualizations for real-time collaboration in AST
- Demonstrate and document methods applied
- Investigate challenging areas and research topics in series of pilots

The main components of this model are shown from different views to include:

1. **The Surrogate Project/Planning Model (this component)**
2. The Project Planning Model for Skyzer
3. Surrogate Mission Model for Skyzer
4. Surrogate System Model for Skyzer
5. Surrogate Acquisition Model Skyzer
6. View and Viewpoints for DocGen and other Libraries

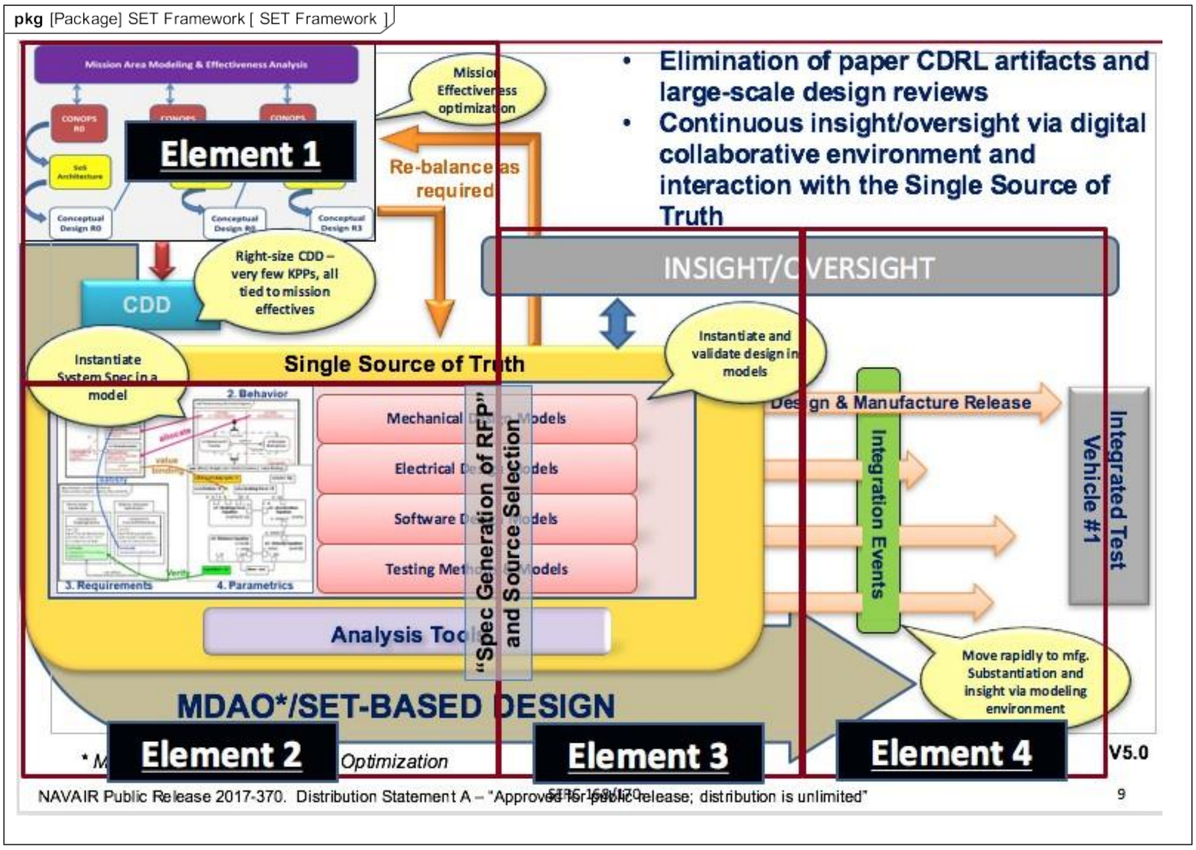
We focus on learning about a new operational paradigm between government and industry in the Execution the SET Framework (NOT an air vehicle design). There are many more detailed facets to the surrogate pilot. The following is a non-exhaustive list of examples that are formalized as mission objectives for the surrogate pilot using a model:

- Simulating prior to contract award
- Formalization of a “specification” for “RFP” and methods for providing models to contractor
- Simulating “Execution” of Oversight / Insight in AST per SET Framework for real-time collaboration in heterogeneous environments
- Objective measures for evaluating evolving design maturity, with the reduction of risk
- Simulating feedback back to mission engineering caused by specified objectives for unachievable KPP
- Simulating approach for “faults in specification/model” detected after contract award

- Simulating source selection – desirably as a dynamic simulations and V&V
- Working with contracts/legal to get agreement on what a "specification" would be
- Methods for modularizing model used to "generate specification"
- How will we use the SETR guide and checklist that NAVAIR uses? And, how will we make recommendations for its evolution
- Applying research concepts such as:
  - Cross-domain model integration
  - Model integrity
  - Ontologies and semantic web technology
  - Use of Multidisciplinary Design, Analysis and Optimization (MDAO)
  - Modeling methods
  - Demonstrations bring this research together using OpenMBEE

A.1.1 Surrogate Pilot Framework

Figure 1.1. Surrogate Pilot Framework



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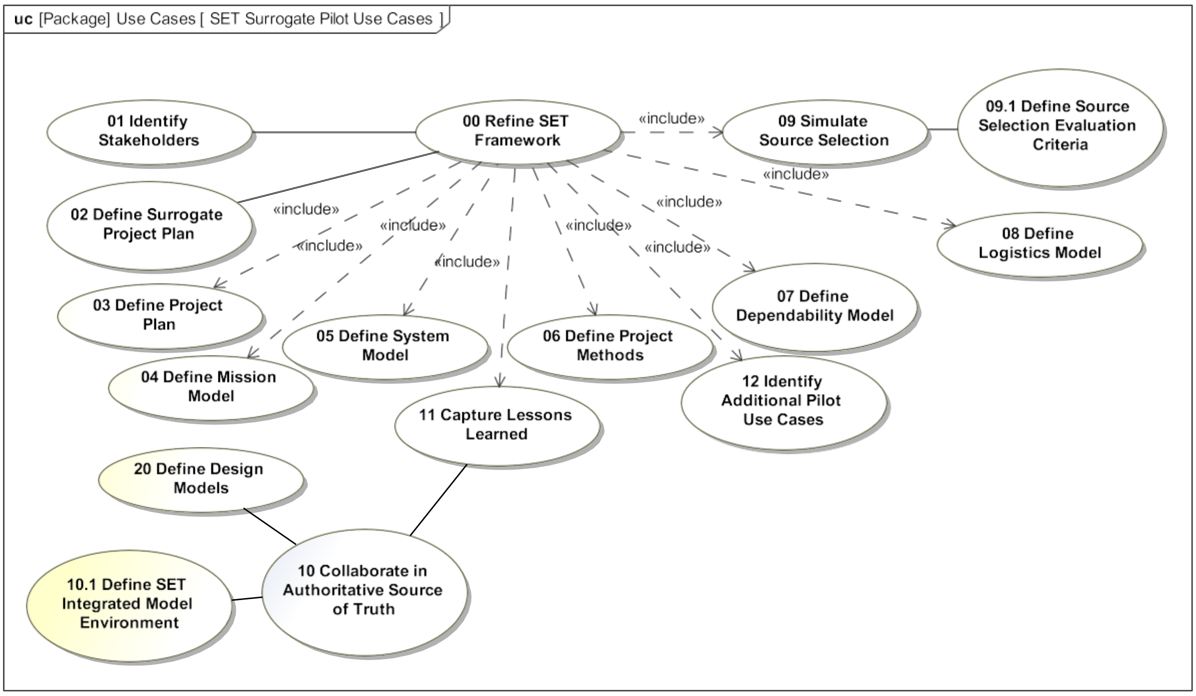
A.1.2 Use Cases

Figure 1.2. SET Surrogate Pilot Use Cases



Notionally, these are the primary use cases that are further defined within this surrogate project plan using a method based on the NASA/JPL Integrated Model Centric Engineering (IMCE) ontologies.

Table 1.1. Use Cases

Model Element	Documentation
00 Refine SET Framework	The main use cases is to Refine the SET Framework using a pilot project for simulating experiments while Executing the SET Framework.
01 Identify Stakeholders	Defined in following sections.
02 Define Surrogate Project Plan	This is what is reflected in this model. It is the plan about how to do Surrogate Experiments for assessing and refining the SET Framework. This document is produced from the model for the SET Surrogate Pilot.
03 Define Project Plan	This is the project plan for the surrogate system, currently referred to as Skyzer.
04 Define Mission Model	The Mission scenarios defined in Skyzer IM20.
05 Define System Model	The System model defined in Skyzer IM30.

06 Define Project Methods	The project methods covering various processes. This is the Skyzer project plan. There is a need to identify a stakeholder that can operate as the lead of the project.
07 Define Dependability Model	This use case is for modeling dependability, which include reliability, safety, etc., and would use modeling techniques based on Hazard Analysis and Failure Modes and Effects Analysis. A stakeholder needs to be identified to support this use case.

Model Element	**Documentation**
08 Define Logistics Model	This is a logistics model. We need to identify stakeholder(s) that can support this use case.
09 Simulate Source Selection	The use case is about simulating the source selection.
09.1 Define Source Selection Evaluation Criteria	This is the source selection evaluation criteria. This will likely evolve through additional pilot use cases.
10 Collaborate in Authoritative Source of Truth	This is the process by which we create and collaborate in the Authoritative Source of Truth (AST). This will involve the surrogate contractor(s) to "integrate" their environments with the NAVAIR surrogate pilot project IME.
10.1 Define SET Integrated Model Environment	This is the Integrated Model Environment (IME) that will be created by the NAVAIR surrogate pilot team, which is based on system modeling tools and OpenMBEE, the open source environment from NASA/JPL.
11 Capture Lessons Learned	This is a general set of lessons learned that we plan to capture from various internal and external stakeholder (e.g., other government organization and industry). This use case may include a more formal request for evaluating the surrogate pilot by directly examining the progress captured in the Authoritative Source of Truth (AST).
12 Identify Additional Pilot Use Cases	Define addition pilot use cases as we proceed through the execution of the first phase of use cases. Other examples include: mission systems, legacy system, Capability-Based Test and Evaluation, etc.
20 Define Design Models	This is the design created by the Surrogate Contractor. There will be many objectives placed on this use case that need to be assessed as part of a new operational paradigm between Government and Industry.

A.1.3 Surrogate Project Modeling Approach

There are several methods used to develop the NAVAIR surrogate pilot models (project, mission, system), and while there are a few traditional system model (SysML) views included in this model, this SET Framework Surrogate Pilot Project model uses the NASA/JPL IMCE ontologies as part of the Systems Engineering Research Center (SERC) research for this project. The figure shows a Partial Map of Foundation Ontology Concepts presented in a Module produced by NASA/JPL's Steve Jenkins. More information can be found here: https://nescacademy.nasa.gov/category/3/sub/17

Some example ontology definitions are included at the beginning of several section to illustrate how the ontology classes provide a basis for creating legal statements (as models) to characterize this project model. For example:

For clarification purposes these definitions were extracted from the NASA/JPL IMCE ontology. The ontologies have been transformed into profiles. Stereotypes from these profiles are used to allow the creation of legal sentences (axioms) about stakeholders, concerns, missions, objectives, projects, requirements, and components that comply with the ontologies. A few examples are provided here.

A Stakeholder is a person or organization with a recognized interest in the successful completion of a Projector Program. Example Stakeholders include: executives, subject matter experts, engineers, and industry contractors.

A Person corresponds to an individual named person. A Person belongsTo zero or more

Organizations.

A Rolecorresponds to a set of assignments meant to be filled by a

single Person. A Mission is a PerformingElement that pursues

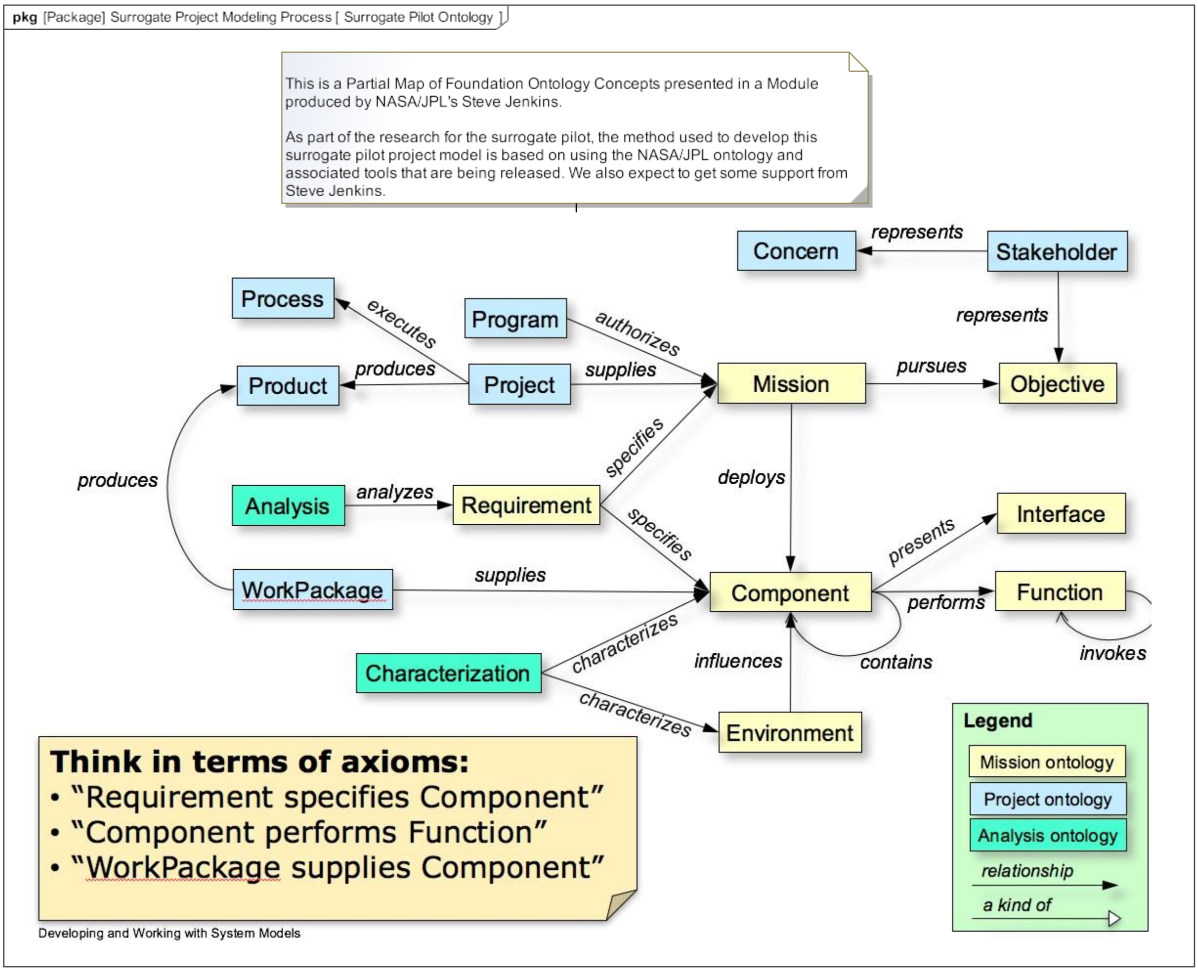
Objectives.

A Missionmay contain Components, but the preferred relationship is that a Missiondeploys its systems (which are Components). This convention allows for a Missionto be associated with shared or external Components that it does not strictly contain.

An Objectiverepresents a specific interest that one or more stakeholders have in the successful execution of a mission. Example Objectives include charactering how to Execute the SET Framework.

Objectives differ from Requirements in that they are not the result of negotiated agreement between customer and supplier, they need not be mutually consistent, and a Missionpursues but need not completely achieve all its Objectives. In a sense, the set of Requirements for a Mission represents the minimum acceptable achievement of Objectivesfor a given cost, schedule, and risk.

Figure 1.3. Surrogate Project Modeling Approach



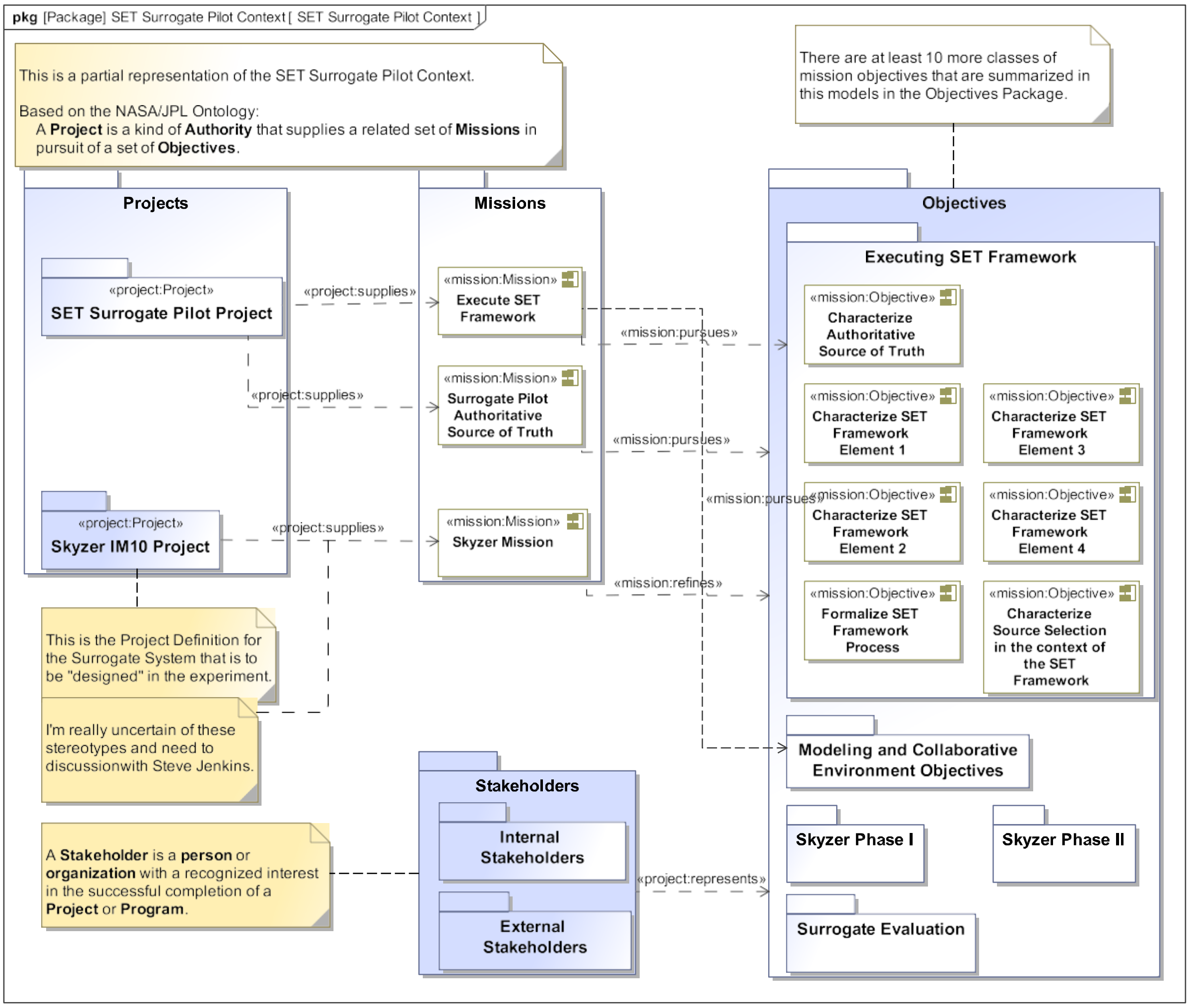
As part of the research for the surrogate pilot, the method used to develop this surrogate pilot project model is based on using the NASA/JPL ontology and associated tools that are being released. We also expect to get some support from NASA/JPL's Steve Jenkins.

A.2 Chapter 2. Surrogate Pilot Context

A.2.1 SET Surrogate Pilot Context

As discussed in Chapter 1, this project plan is modeled to comply with the NASA/ JPL IMCE ontologies. A Projectis a kind of Authoritythat supplies a related set of Missions in pursuit of a set of Objectives. Stakeholders represent Objectives.

Figure 2.1. SET Surrogate Pilot Context



A.2.2 Stakeholders

Stakeholders exist in the model, but are not exposed per the guidance of NAVAIR.

A.2.3 Concerns

A Concernrepresents a specific interest that one or more Stakeholders have in the successful completion of a Projector Programand its Missions.

A Missionis a PerformingElementthat pursues Objectives.

An Objectiverepresents a specific interest that one or more stakeholders have in the successful execution of a mission. Example Objectives include charactering how to Execute the SET Framework.

For this reason, and because we are formalizing objectives in this model, many of the concerns have been formalized as more specific objectives that need to be characterized throughout this effort

Objectives are elaborated in the following chapter.

A.2.4 Assess and Refine SET Framework

Table 2.1. Assess and Refine SET Framework

Model Element	Documentation
Must right size the Capability Description Document	Some examples characterized by Dave Cohen: 1. Narrow top of the requirements pyramid 2. Off-load requirments to other elements of SoS and via TTPs (CONOPS) 3. KPPs must be tied to mission effectiveness, Ao or Cost
The Systems Engineering Technical Reviews events takes too long	The traditional process for performing Systems Engineering Technical Review (SETR) events takes too long, happens too late, and does not take advantage of capabilities that would permit more continuous and asynchronous events.
Time to develop capabilities is too long	The time it takes to get new capabilities into the field is not keeping pace with the changing threats.

A.2.5 Modeling and Collaboration Environment Concerns

Table 2.2. Modeling and Collaboration Environment Concerns

Model Element	Documentation
Ability to ensure Enterprise Governance to Modeling Environment	
Ability to share with stakeholders	
Ability to work and collaborate in an unclassified environment	
Ability to work and collaborate in classified environment	

A.3 Chapter 3. Surrogate Pilot Objectives

This section starts from the Mission perspective of the SET Framework Execution. This section is evolving and presents a non-exhaustive set of mission objectives for Executing the SET Framework. These objectives will be defined and related, and there will be traceability created to show how the objectives are satisfied during the execution of the SET framework through the development of the Mission, System, and Design models.

The model representations used in this section are based on the NASA/JPL Mission ontology, which defines concepts for describing missions in terms of:

- Objectives (this section)
- Constituent components
- Functions those components perform
- Requirements that specify them

The objectives are organized into about 10 classes that are presented in subsections of the chapter. Each subsection has one or more models (diagram) of the objectives that associate key stakeholder(s) with one or more objectives. These models formalize information and relationships that have been evolving in Power Point briefings. At the end of each section is a table that provides more information about each objective.

Objectives differ from Requirements:

- They are not the result of negotiated agreement between customer and supplier
- They need not be mutually consistent
- A Mission pursues but need not completely achieve all its Objectives

A.3.1 Executing SET Framework Objectives

Figure 3.1. Executing SET Framework

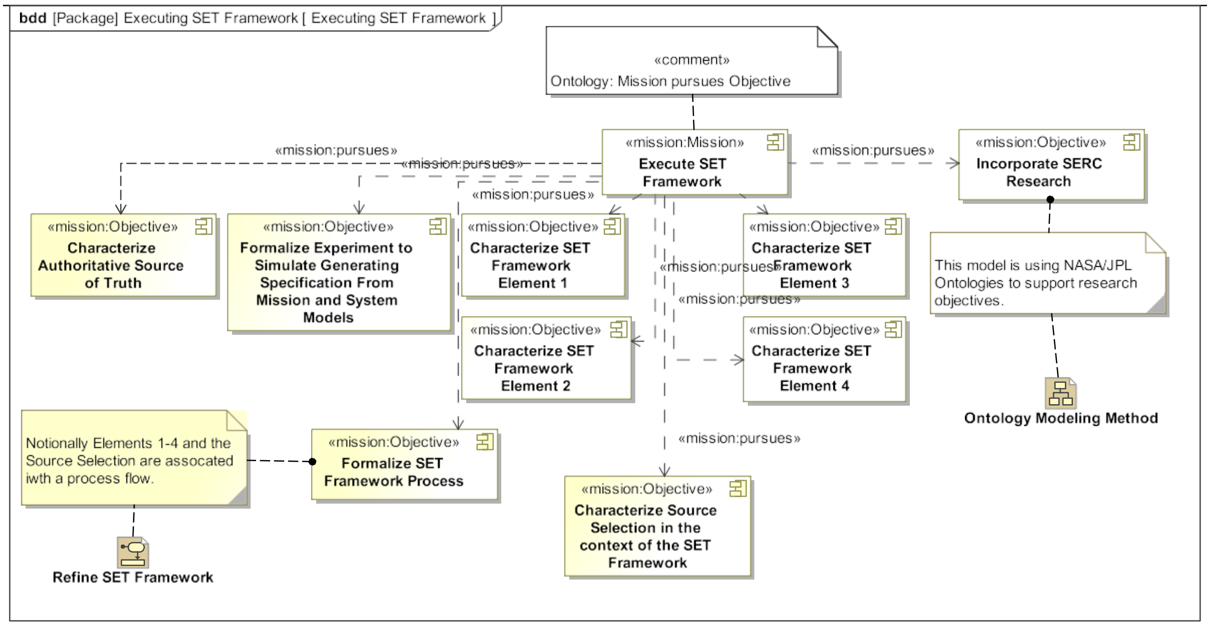
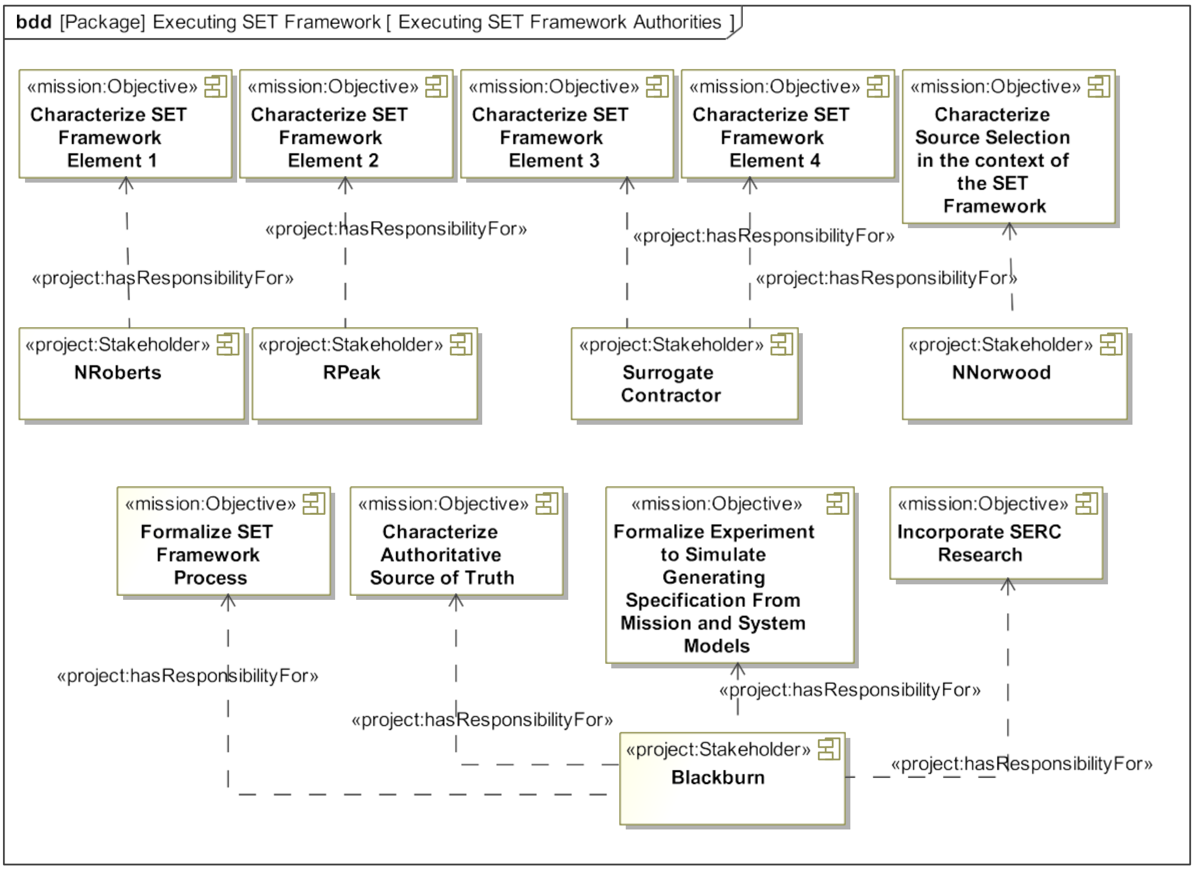


Figure 3.2. Executing SET Framework Authorities



This view uses the <<project:hasResponsibilityFor>> relation to show those project stakeholders that have the primary responsibility for mission objectives.

Table 3.1. Executing SET Framework Objectives

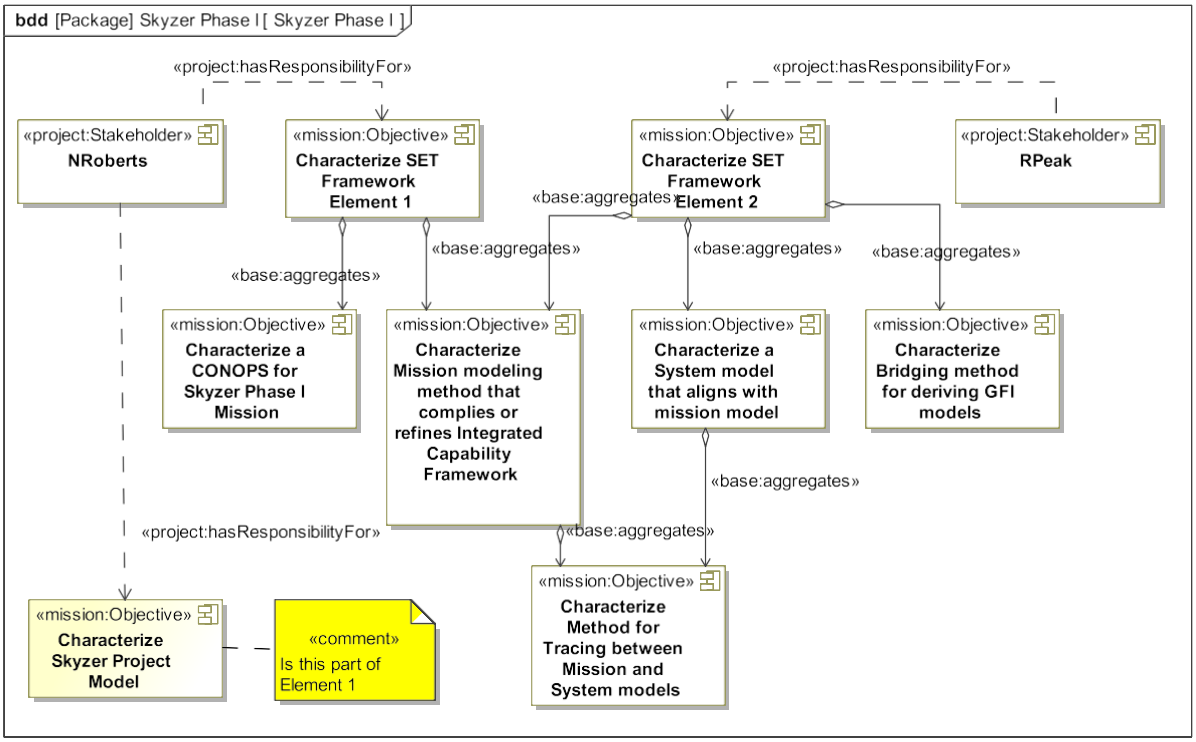
Model Element	Documentation
Characterize Authoritative Source of Truth	Develop a prototype infrastructure that can be used by both Government/SERC team to support Element 1 & 2, and that can also be "integrated" while conducting

	Insight/Oversight for collaboration with Surrogate contractors in Element 3 & 4.
Characterize SET Framework Element 1	Element 1 is fundamentally about mission modeling, but has other aspects. For example, does it include how the Integrated Warfare Analysis establishes CONEMPS and Effects-Chains and how they are modeled at the System of Systems (SoS) level? Therefore the objective is about characterizing all facets associated with Element 1.
Characterize SET Framework Element 2	Element 2 is also fundamentally about developing a System Model, synthesizing a specification, but it also factors in aligning the system model with the mission model and Key Performance Parameters.
Characterize SET Framework Element 3	Element 3 starts when the contract has been awarded. Element 3 is where the contractor refines the design awarded under contract. The key aspects for the pilot is to understand how subject matter experts from NAVAIR are able to view, measure maturing designs

Model Element	Documentation
	in a collaborative environment (the AST). In addition, the pilot seeks to assess new operational approaches to contract modifications that are performed directly in models.
Characterize SET Framework Element 4	It is unclear what happens in Element 4.
Characterize Source Selection in the context of the SET Framework	The objective is to perform source selection in the context of models. The objective is to have the Government Furnish Information (models) that are provided as part of the RFP, be elaborated, corrected and refined by the surrogate contractors. We need to characterize exactly when this happens between Element 2 and Element 3 and all of the rules that govern Industry and Government collaboration.
Formalize Experiment to Simulate Generating Specification From Mission and System Models	This section of the model is characterizing many of the objectives that need to be formalized as experiments, for determining how mission and system models are used to generate a "specification" directly from models. The objective should potentially go beyond what might actually be needed in terms of modeling to demonstrate "how" rigorous and comprehensive modeling can be done. The experiments must also "seed" defects in the RFP delivered models to allow for understanding potential change management approaches in model-based acquisition under the SET Framework.
Formalize SET Framework Process	While it may not actually be necessary or possible to fully characterize the SET Framework Process, there are research merits to illustrate the concept of a process model, especially specific types of feedback loops that are related to operational interactions between the Government and the Surrogate contractor.
Incorporate SERC Research	The key research topics are: cross-domain model integration, model integrity, modeling methods, ontologies and many derived topics such as working collaboratively an authoritative source of truth (AST), which leads into the Integrated Modeling Environment (IME). A key reason for creating this type of model for the SET Surrogate Pilot project is to satisfy research requirements characterized in the SERC research task for the SERC collaborators.

A.3.2 Skyzer Phase I Objectives

Figure 3.3. Skyzer Phase I



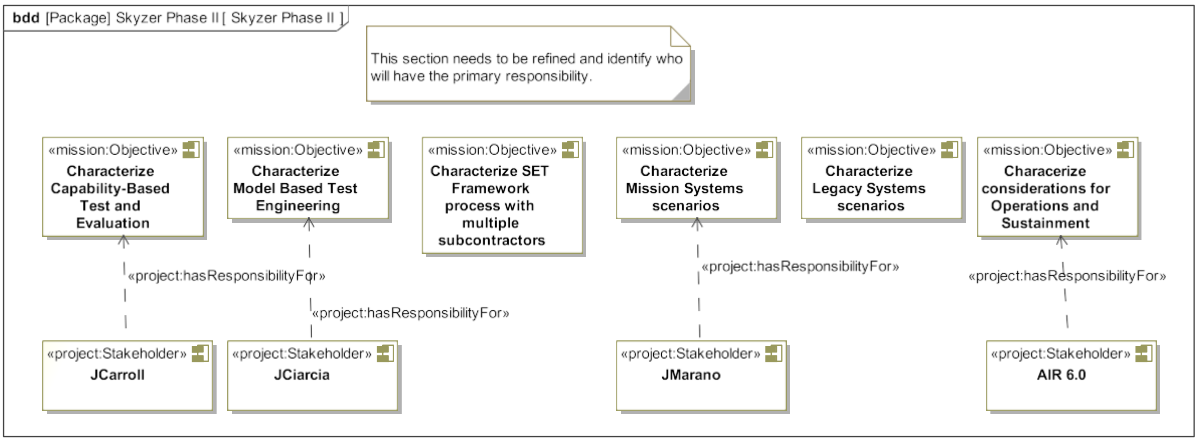
This model illustrates the <<base:aggregates>> relation from the IMCE ontologies, which provides a means to relate objectives.

Table 3.2. Skyzer Phase I Objectives

Model Element	Documentation
Characterize a CONOPS for Skyzer Phase I Mission	This should define the CONOPS that will be refined by the Mission Model.
Characterize a System model that aligns with mission model	This is the system model that will be used with Bridging method/mechanism to produce both the generated specification as well as the Government Furnished Information (GFI) that will be part of the Request for Proposal (RFP) and used in source selection.
Characterize Bridging method for deriving GFI models	This is a concept for taking analysis derived modeling and bridging the specific information that is needed to go into a Government Furnished Information (GFI) model for purpose of Request for Information (RFI), Request for Proposal (RFP) and/or source selection.
Characterize Mission modeling method that complies or refines Integrated Capability Framework	The current approach for performing mission area analysis is based on the Integrated Capability Framework. This objective should demonstrate how model support or subsumes these guidelines.
Characterize Skyzer Project Model	The objective is to define the Skyzer Project modeling guidelines, which currently includes the characterization of mission and system modeling methods. Does this occur in Element 1?

A.3.3 Skyzer Phase II Objectives

Figure 3.4. Skyzer Phase II



Scott is lead for the SET Framework Links.

Table 3.3. Skyzer Phase 2 Objectives

Model Element	Documentation
Characterize considerations for Operations and Sustainment	Determine what type of information should be captured during the early stages of SET Element 1 and 2 phases that will better help with Operations and Sustainment.
Characterize Capability-Based Test and Evaluation	This is the concept discussed by Jim Carroll. The objective is to bring this capability in early and understand the implications on process. This may have impacts on source selection criteria.
Characterize Legacy Systems scenarios	This objective looks to evaluate and characterize how the SET Framework should be used for legacy systems. This particular question came from industry during briefings on the surrogate pilot.
Characterize Mission Systems scenarios	There is a belief that most ongoing changes and future changes will involve mission systems, and Phase 2 of the surrogate pilot should be structure like a block upgrade, which provides an opportunity to provide scenarios for involving Mission Systems for the flight vehicle.
Characterize Model Based Test Engineering	This should bring in the capabilities of the Model Based Test Engineering research performed by Jim Ciarcia. This includes metamodels that represent and ontology for many phases of this process. The addition objectives are to bring these concepts in early.
Characterize SET Framework process with multiple subcontractors	

A.3.4 Modeling Methods Objectives

Figure 3.5. Modeling Methods

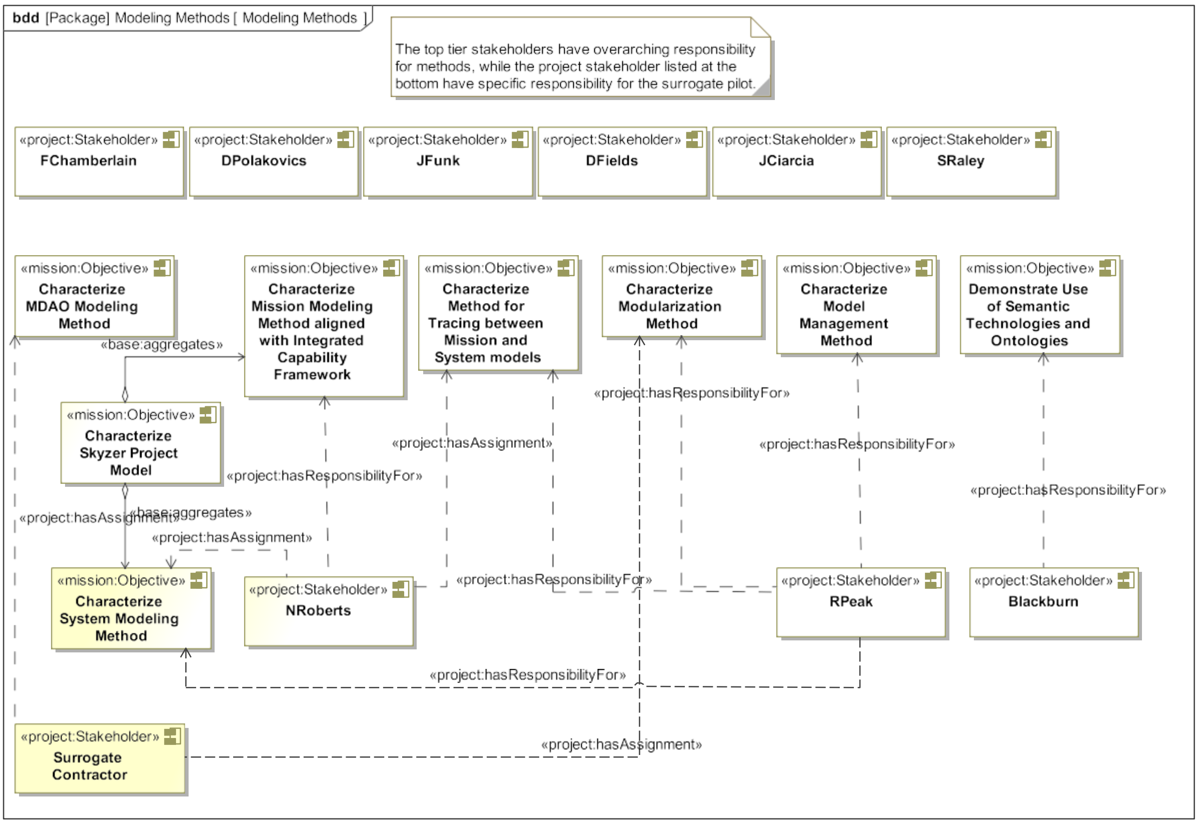


Table 3.4. Modeling Methods Objectives

Model Element	**Documentation**
Characterize MDAO Modeling Method	The method for Multidisciplinary Design, Analysis and Optimization (MDAO) has been demonstrated in the SERC RT-168 research for CONOPS and system-level modeling. This objective seeks to characterize this through the use of examples and demonstrations for the surrogate pilot, and will carry this out using Phoenix Integration ModelCenter for the SERC researchers, but the Surrogate Contractor has their own MDAO tools.
Characterize Method for Tracing between Mission and System models	Need to characterize how the surrogate contractor can extend the system model and trace to discipline/ domain-specific models, which also traces back up to the mission model. Should this also trace to CONOPS or CONEMPS? In the context of the model management method, where should the traceability linkages be created?
Characterize Mission Modeling Method aligned with Integrated Capability Framework	The objective is to defined a mission modeling method that aligns with the Integrated Capability Framework. This characterizes the processes for Mission Technical Baseline and the Integrated Capability Technical Baseline.

Model Element	Documentation
Characterize Model Management Method	The objective is to define one or more model management methods that can support a new operational paradigm specifically focused on new approaches to contracting that can operation more like software change control. We use the native No Magic Project Uses mechanism. This allows one or more models to be referenced by the including model. This is currently used in the following way: • The System Model includes the Mission Model in order to show traceability from the System Model to the Mission Model • Most models include the Viewpoint libraries (usually and IM90 model name) • We expect the Contractor to include the System Model when it refines or extends the System Model, but also provides traceability to System Mode. • We are also working with NASA/JPL to also look at the best approaches for Model Management using MMS.
Characterize Modularization Method	
Characterize System Modeling Method	This characterizes the system modeling method. The initial recommendation was to use OOSEM, but can this apply to all type of programs?
Demonstrate Use of Semantic Technologies and Ontologies	There are many objectives for using Semantic Technologies and ontologies for formalizing methods and to support cross-domain model integration through interoperability of ontologies data. In addition, this particular model element is based on the NASA/JPL IMCE ontologies.

A.3.5 Real-time Collaborate in AST Objectives

Figure 3.6. Real-time Collaboration in AST

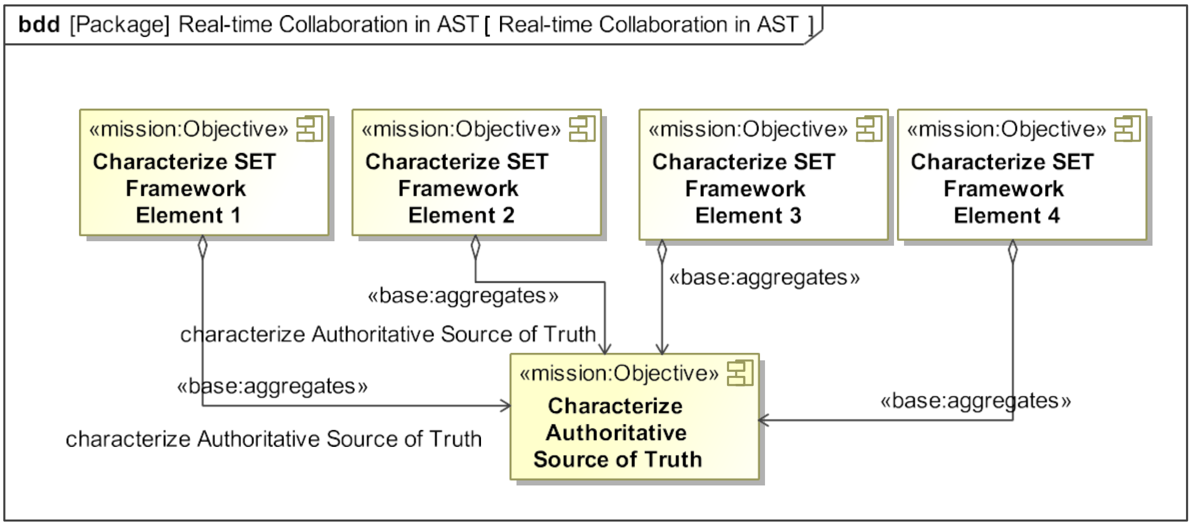
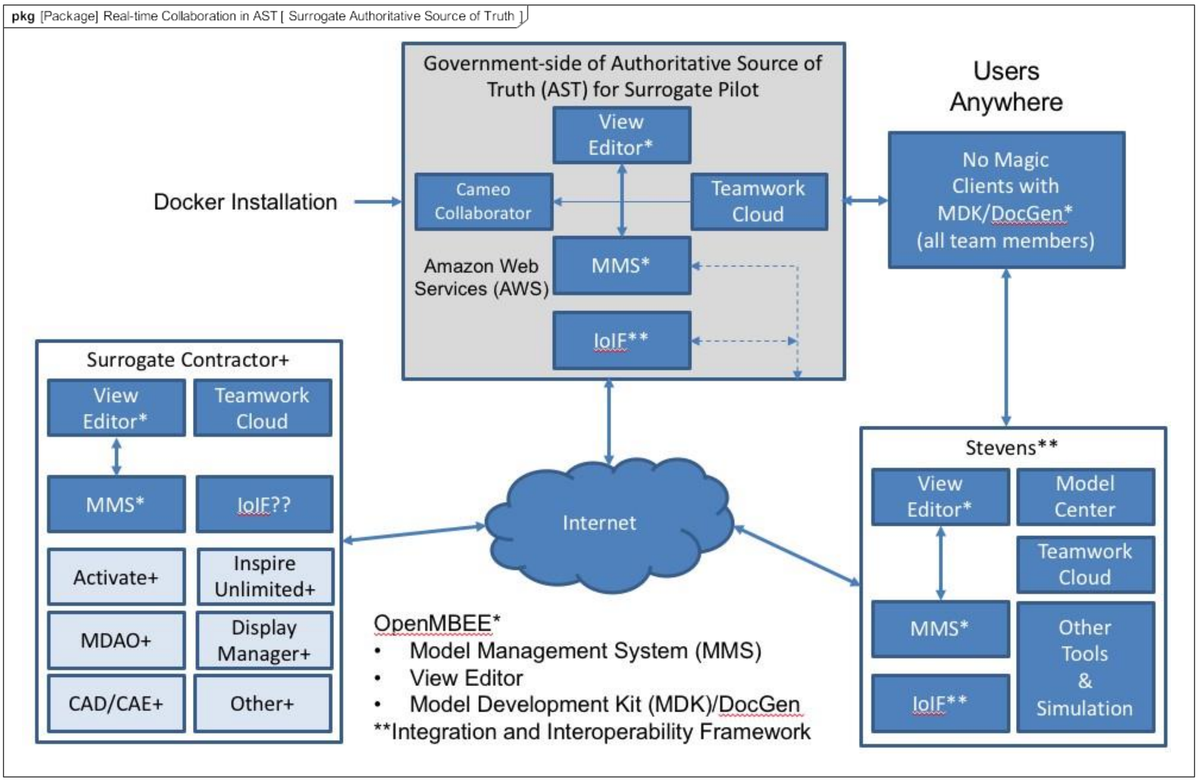


Figure 3.7. Surrogate Authoritative Source of Truth



This is a rendering of the some of the elements that make up the distributed Authoritative Source of Truth (AST) we are using for the Surrogate Pilot.

We have installed the OpenMBEE environment using Docker, which is a mechanism that uses one script to install the Model Management System (MMS) and View Editor. This is hosted on Amazon Web Services (ASWS) (ime.sercuarc.org). We also have on AWS a Teamwork Cloud repository of the various models. The team members can connect to these elements though a No Magic modeling client (e.g., MagicDraw or Cameo). The Model Development Kit (MDK) is a plugin for the No Magic Client, which include support for DocGen and access to MMS.

The Docker capability not only allows for the Government to provide the actual models as Government Furnished Information (GFI), but also allows the exact environment used by the Government team to be provided to the Surrogate Contractor.

The last capability is called the Integration and Interoperability Framework (IoIF), which is part of our research to make connections to other capabilities in our research, such as a Decision Framework (see RT-168 Technical Report).

Figure 3.8. Use Cases for Collaboration Environment and Authoritative Source of Truth

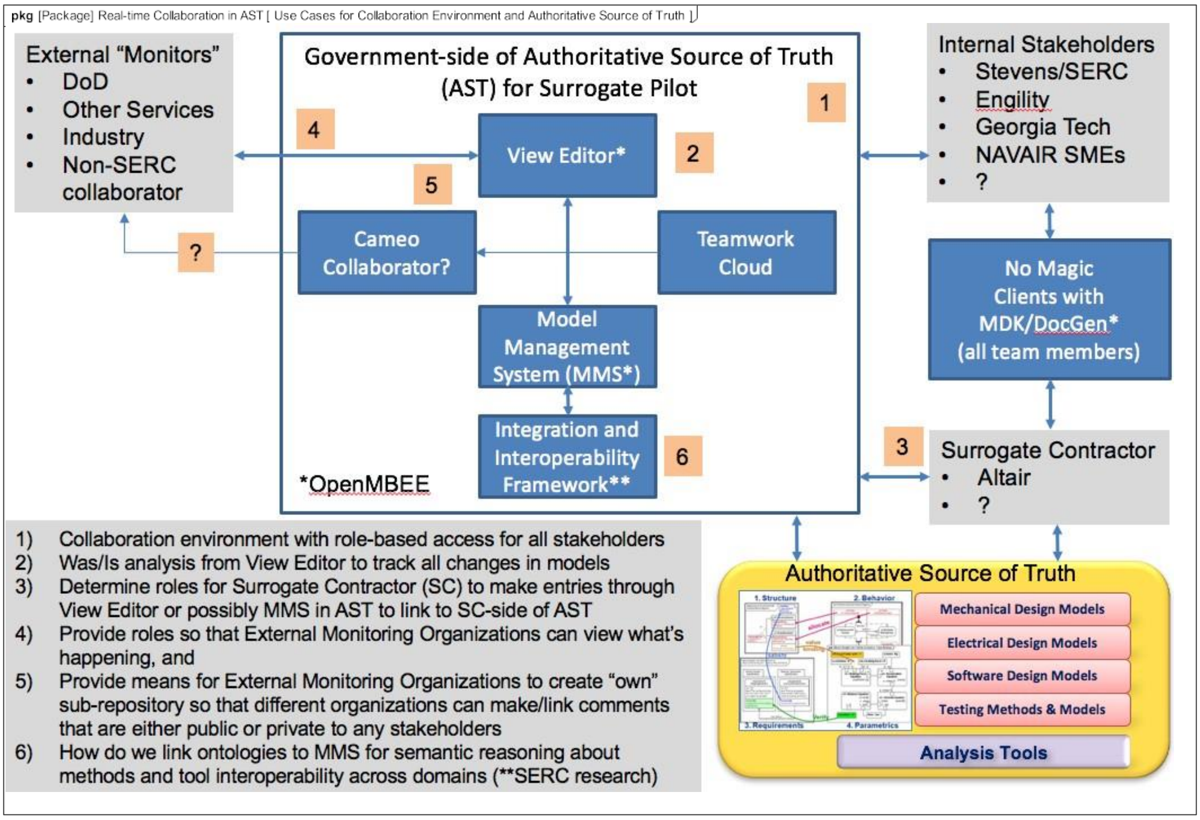


Table 3.5. Real-time Collaborate in AST Objectives

Model Element	**Documentation**
Characterize Approach for Integrating Government and Industry Environments in AST	This will include, but not be limited to: 1. Collaboration environment with role-based access for all stakeholders 2. Was/Is analysis from View Editor to track all changes in models 3. Determine roles for Surrogate Contractor (SC) to make entries through View Editor or possibly MMS in AST to link to SC-side of AST 4. Provide roles so that External Monitoring Organizations can view what's happening, and 5. Provide means for External Monitoring Organizations to create "own" sub-repository so that different organizations can make/link comments that are either public or private to any stakeholders 6. How do we link ontologies to MMS for semantic reasoning about methods and tool interoperability across domains (**SERC research)
Characterize Process for Insight and Oversight in AST	
Package Modeling Environment as part of Collaboration	The concept is to use Docker in order to allow the development environment used to produce the Initial System Model to be shared with the Surrogate Contractor.
Set up Collaborative Environment for AST	

Model Element	Documentation
Use of OpenMBEE MMS to Demonstrate Model Management	A key driver for NASA/JPL developing OpenMBEE was to provide model management at a fine level of granularity and be completely tool agnostic. This should provide a means for providing details tracking of changes that can support a new operational paradigm for managing contracts.

A.3.6 Decision Framework Objectives

Figure 3.9. Decision Framework

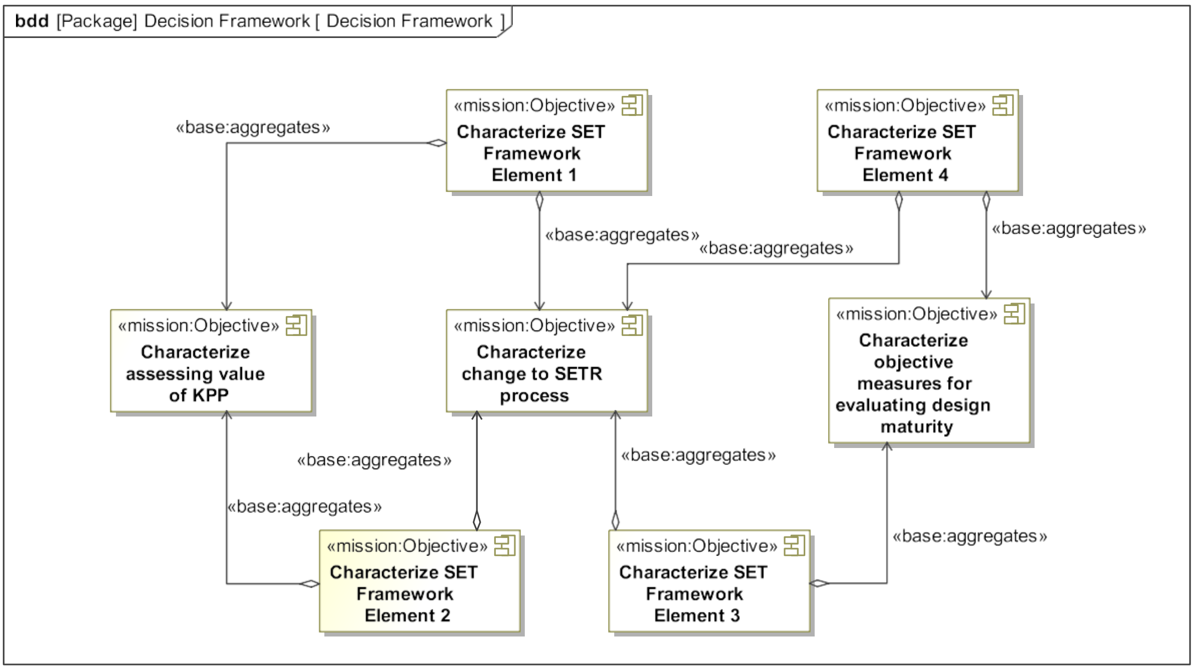


Table 3.6. Decision Framework Objectives

Model Element	Documentation
Characterize assessing value of KPP	A possible Decision Framework research tool and method for assigning value to KPPs is being applied to different case studies on the ARDEC research task RT-168.
Characterize change to SETR process	This objectives investigate how the SETR process/ guidebook/checklist can be refined or modified by being able to make assessments more objectively within models. There is research that has started an ontology from the SETR guidebook. Can this be part of the objectives measures?
Characterize objective measures for evaluating design maturity	This is a new process to allow for continuous asynchronous decision making about a maturing design as opposed to the traditional monolithic events (e.g., SRR, PDR, CDR). It is unclear if the objective measure apply to Element 1 or 2.

A.3.7 Source Selection Objectives

Figure 3.10. Source Selection

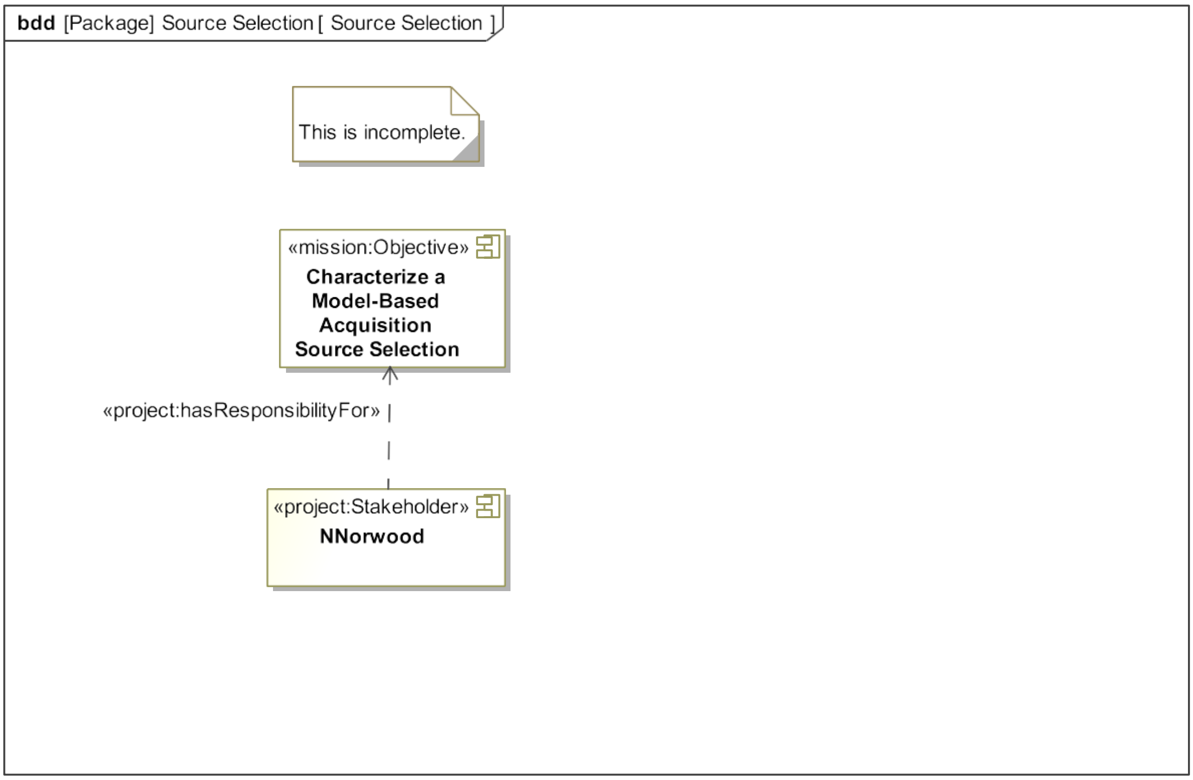


Table 3.7. Source Selection Objectives

Model Element	Documentation
Characterize a Model-Based Acquisition Source Selection	This description still needs refinement. The source selection process occurs after a Request for Proposal (RFP) has been issued. We envision this process will include: 1. Mission Model View 2. System Model View 3. System Model (as Government Furnished Information) 4. Statement of Work (SOW) 5. Section L

A.3.8 Operations and Policy of Contracting Objectives

Figure 3.11. Operations and Policy of Contracting

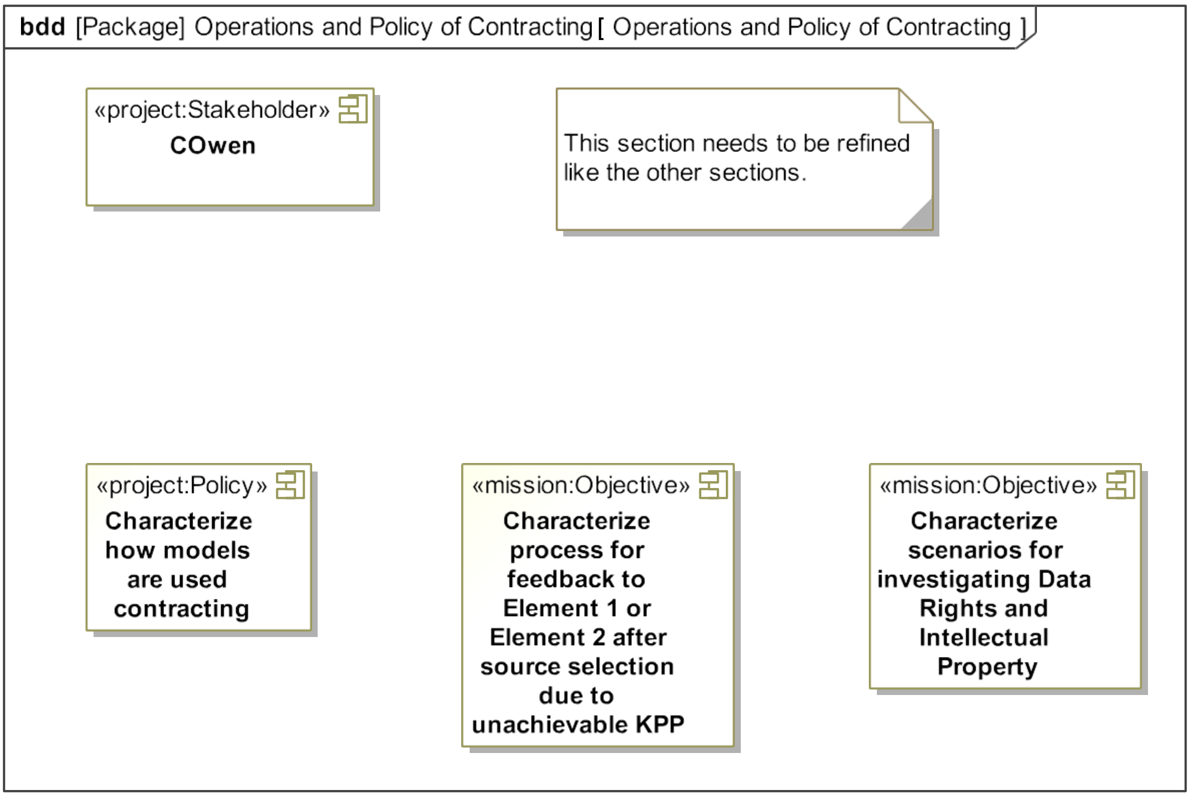


Table 3.8. Operations and Policy of Contracting Objectives

Model Element	Documentation
Characterize how models are used contracting	Investigate the potential
Characterize process for feedback to Element 1 or Element 2 after source selection due to unachievable KPP	The objective is to determine processes enabled by modeling and all association enabling technologies for contracting related feedback due to issues in the contract after source selection.
Characterize scenarios for investigating Data Rights and Intellectual Property	Consider looking at the document from the Aerospace Industry Association CONOPs. Who owns the different models? Recall the approach used by NAVSEA and Huntington Ingalls called the Product Data Model (PDM) that was presented at the 2016 Model Centric Engineering Government and Industry Day.

A.3.9 Visualization Objectives

Figure 3.12. Visualization

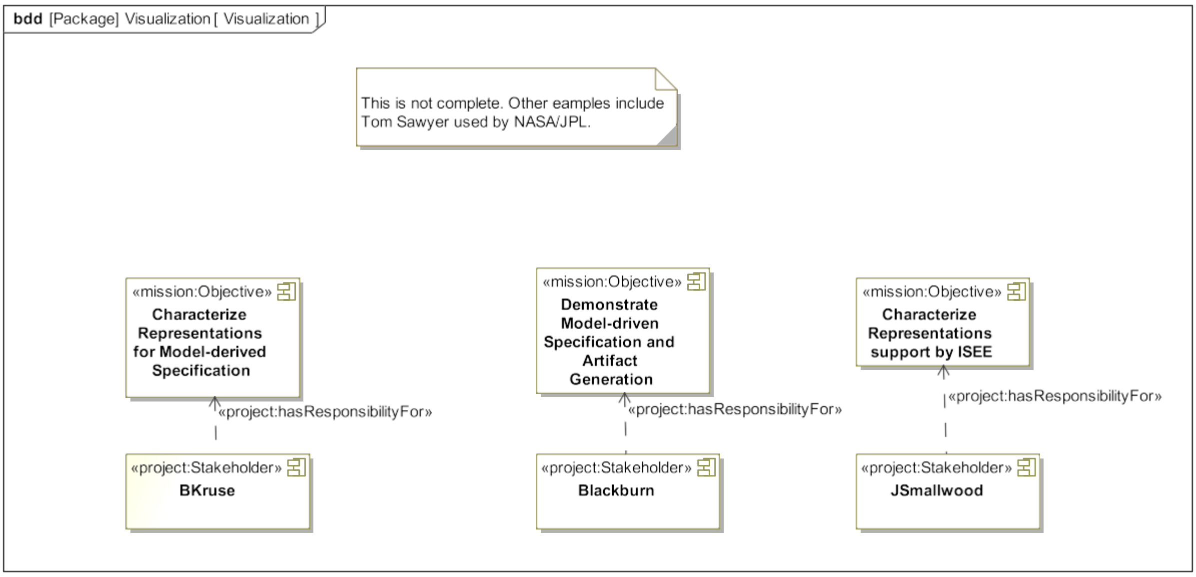


Table 3.9. Visualization Objectives

Model Element	Documentation
Characterize Representations for Model-derived Specification	
Characterize Representations support by ISEE	These are existing mechanisms that will support visualizations.
Demonstrate Model-driven Specification and Artifact Generation	The objective is to demonstrate the uses of model-driven specifications to support contracting as well as other artifacts to provide the appropriate view and viewpoints relevant to different stakeholders.

A.3.10 Surrogate Evaluation Objectives

Figure 3.13. Surrogate Evaluation

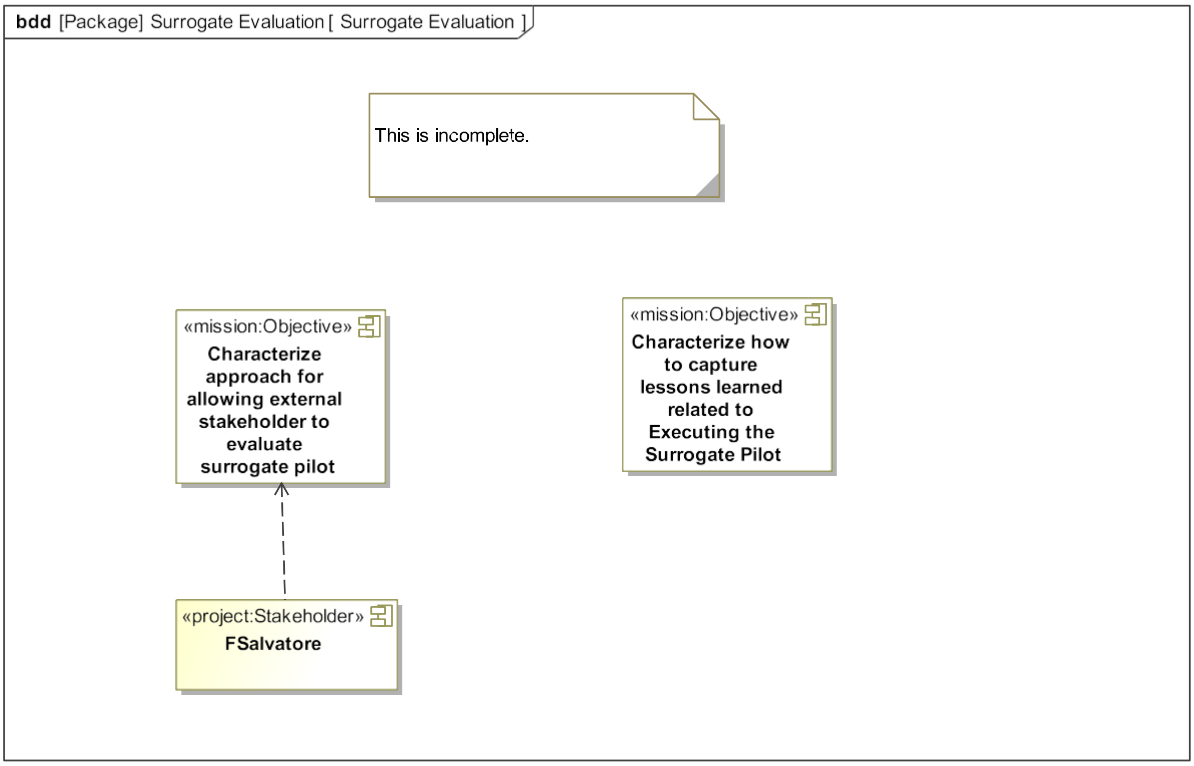


Table 3.10. Surrogate Evaluation Objectives

Model Element	Documentation
Characterize approach for allowing external stakeholder to evaluate surrogate pilot	This needs to refine the idea that we can selectively allow external stakeholders permission to log in to the Authoritative Source of Truth repository and provide ongoing feedback to all facets of the approach used on various phases of surrogate pilot.
Characterize how to capture lessons learned related to Executing the Surrogate Pilot	We need to characterize how we are going to capture lessons learned during the execution of numerous phases of this pilot, including capturing (potentially) anonymously information from external stakeholders such as Industry and Govenment organizations other than NAVAIR.

B. University of Maryland Ontology Research

Project Researcher: Mark Austin

Graduate Student: Maria Coelho (Ph.D. candidate) (funded by SERC RT195).

Reporting Period: February 16, 2018, through February 15, 2019.

Role of UMD in RT 195.

The University of Maryland (UMD)'s role in RT 195 is to explore opportunities for supporting the SET framework with semantic technologies for reasoning about completeness and consistency of system entities (e.g., textual requirements, mathematical constraints, elements of system structure and behavior) across a multiplicity of domains relevant to the surrogate (Skyzer) pilot case study problem.

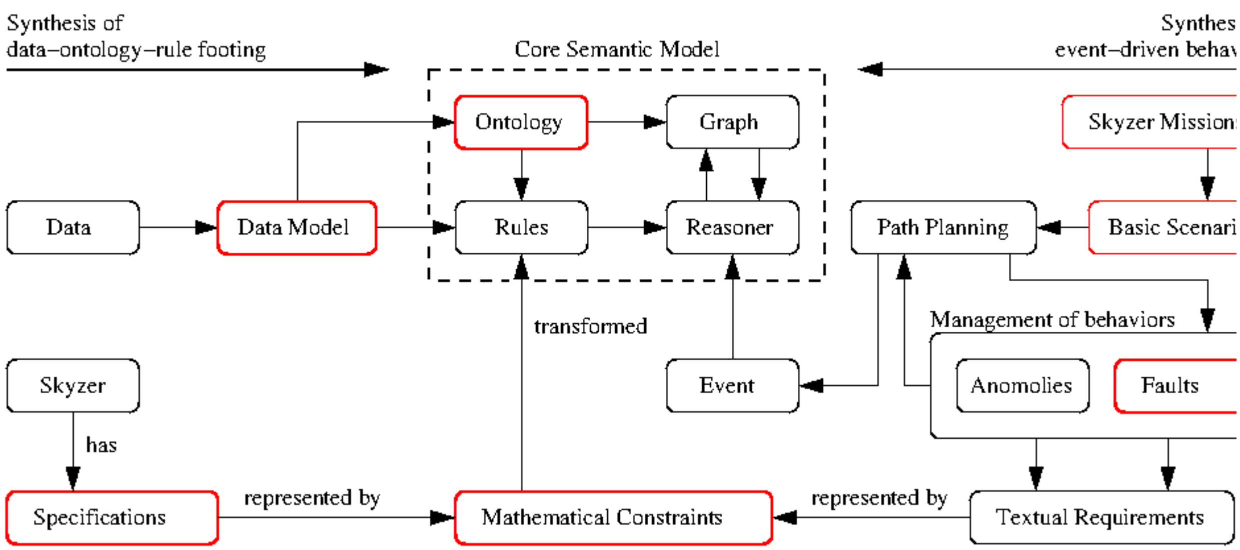


Figure 1. Simplified schematic for data-driven development and semantic modeling of multi-domain systems. Focus areas are highlighted in red.

In a departure from previous efforts in semantic modeling of multi-domain environments, our investigation has focused on exploring opportunities in putting: (1) data, ontologies, and rules on an equal footing, and (2) creating semantic frameworks that will accept sequences of events generated by tasks associated with mission operations. Figure 1 illustrates the relationship of these two directions of work to a centralized multi-domain semantic model and reasoning capability.

Our research efforts for RT 195 have been organized into two mini-projects:

B.1 PROJECT 1. Computational Infrastructure for the Data-Ontology-Rule Footing

Research Team: Maria Coelho and Mark Austin.

Project Summary. State-of-the-art approaches to semantic modeling focus on the comprehensive development of domain-specific ontologies, with less effort placed on the development of rules for verification of modeling completeness and/or how the control of interactions and dependencies among domains. Other than acting as a comprehensive representation of a domain, too often the ontologies end up not doing to much. This mini-project has explored opportunities (and potential benefits) of putting data, ontologies and rules on an equal footing and then developing software infrastructure for the specification of mathematical constraints and functional / performance specifications associated with system components (e.g., a drone).

Result A: The Data-Ontology-Rule Footing. Figure 2 builds upon Figure 1 and shows how collections of domain-specific data-ontology-rule footings come together to create a multi-domain semantic environment to support design, execution and validation / verification of Skyzer drone operations.

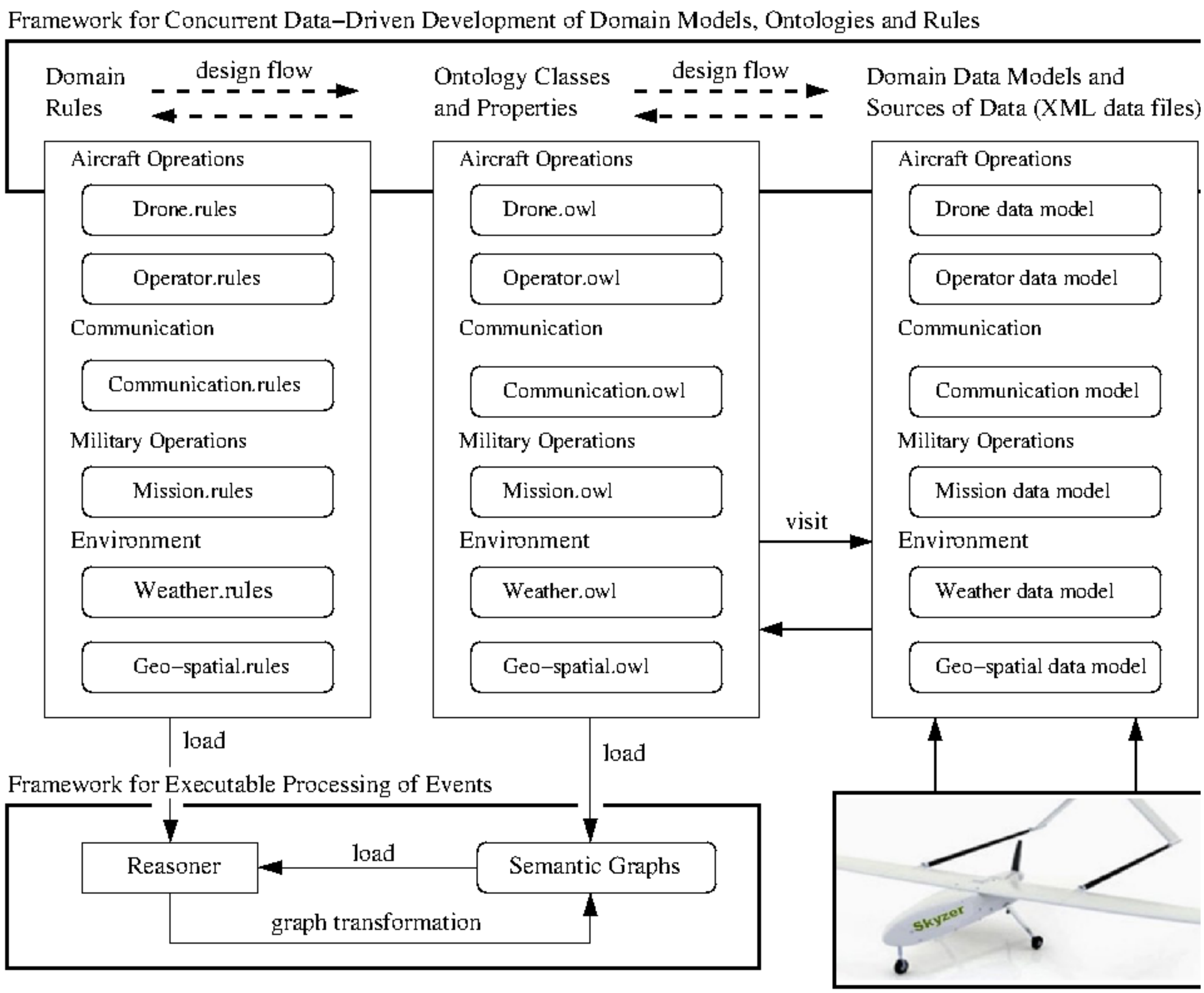


Figure 2. Semantic framework for data-driven development of multi-domain systems.

To overcome limitations of previous research and development efforts in semantic modeling of large-scale engineering systems, our investigation was based on five principles:

- Put ontologies, rules and data on an equal footing.
- Domain ontologies use, but do not extend foundation level ontologies.
- Ontologies visit data models to get the data and object relationships for individuals.
- Semantic graphs dynamically respond to incoming events.
- Enhance power of rules with backend functions.

A key benefit in putting rules on the same footing as ontologies is that it forces semantic model developers to think about the data and object relationships that will need to be in place in order for the rules to work. It is important to note that rules operate on both semantic relationships and individuals created from real-world data. Thus a chain of bi-directional dependency relationships extends completely across Figure 2. We have found that the implementation semantic individuals and subsequent rules is complicated by the small number (less than 10) of basic data types available for semantic modeling. This means that more complicated real-world entities and rule operations (e.g., involving low level temporal or spatial data) are most likely best handled with backend functions. Figuring out how these functions should be organized – perhaps into executable rule libraries – is a major challenge.

One potential downside of the proposed approach (as illustrated along the right-hand side of Figure 2) is that the development of separate data models and their corresponding domain-specific parsers (to read the data into the model) could be an enormous amount of work. Certainly, 15 years ago such an approach would require a significant investment – months of work; thousands of lines of parser code -- just to create a prototype simulation. During the past decade, however, two developments open doors to a much easier pathway forward. First, we can borrow ideas from the Open Street Map (OSM) formalism. With only three types of tag -- <node>, <way> and <relation> and a judicious use of attribute storage mechanisms, the OSM data model can represent the "static" multidisciplinary details of entire cities. This is actually very impressive. A second key development is JAXB, the XML binding for Java, which moves the focus on model development from a complicated domain-specific parser to the careful organization of data model code plus annotations in Java. You cannot overstate the power of this new approach – Google uses JAXB to import data into its Google Maps program – and the opportunities it affords.

Instead of developing separate data models for the individual domains shown along the right-hand side of Figure 2, we have developed a prototype system level data model (SystemDataModel) that is domain agnostic. Like OSM, our system data model employs <node>, <way> and <relation> tags, but adds new entities -- <attribute>, <parameter>, <component>, <specification> and <behavior> -- for the representation of components (e.g., Skyzer) having both structure and behavior. Thus in terms of Skyzer Mission operations, out goal is to cover the drone, operator, communication, mission and lower-level scenario and path data models with one unified system data model. Weather and geo-spatial data would come from external servers.

Result B: Mathematical Constraints and Functional / Performance Specifications. A key element of the vision illustrated in Figure 1 is the ability to represent and evaluate mathematical constraints. Mathematical constraints can be represented and evaluated (details not given) for various types of equality, inequality, logical and relational constraints. Such constraints form the basis of component specifications, guard conditions in state chart behavior models, and provide support for the mathematical representation of textual requirements. Our experimental software allows for the specification of parameters that act across a multiplicity of constraints and specifications, followed by their evaluation.

```
<!-- ================================== -->
<!-- Part 03: Drone component model      -->
<!-- ================================== -->

<component ID="Drone-X47-B" type="UAV">
    <description text="NAVAIR X47-B Drone" />

    <!-- ============================================== -->
    <!-- Component attributes                           -->
    <!-- ============================================== -->

    <attribute key = "length"       value =    "5.5" units = "m" />
    <attribute key = "wingspan"     value =   "10.0" units = "m" />
    <attribute key = "maxRange"     value =  "3,889" units = "km" />
    <attribute key = "maxSpeed"     value =  "1,073" units = "km/hr" />
    <attribute key = "maxEndurance" value =    "6.0" units = "hr" />
    <attribute key = "maxAltitude"  value = "43,000" units = "ft" />

    <!-- ============================================== -->
    <!-- Component state parameters                     -->
    <!-- ============================================== -->

    <parameter name =     "speed" value =   "200.0" units = "m/sec" type = "Real"/>
    <parameter name =    "weight" value =     "0.0" units = "kg"    type = "Real"/>
    <parameter name =  "altitude" value =  "2500.0" units = "m"     type = "Real"/>
    <parameter name =     "range" value = "4,500.0" units = "km" type = "Real"/>
    <parameter name = "endurance" value =     "0.0" units = "hr" type = "Real"/>
    <parameter name =  "latitude" value =     "0.0" />
    <parameter name = "longitude" value =     "0.0" />

    <!-- ============================================== -->
    <!-- Reference to statechart model of drone behavior -->
    <!-- ============================================== -->

    <behavior ID="#B001" />

    <!-- ================================================= -->
    <!-- Drone specifications and measures of effectiveness -->
    <!-- ================================================= -->

    <specification ID = "S01" type = "Performance" >
        <description text="Maximum takeoff weight" />
        <attribute key  = "expression" value = "weight &lt; maxWeight" />
        <parameter name =  "maxWeight" value = "20,215" units = "kg" />
        <parameter name = "#weight" />
    </specification>

    <specification ID = "S02" type = "Performance" >
        <description text="Maximum re-fueled range" />
        <attribute key  = "expression" value = "range &lt; maxRange" />
        <parameter name = "#maxRange" />
        <parameter name = "#range" />
    </specification>
```

Figure 3. Preliminary data model for a drone containing declaration of attributes and parameters

Figure 3 shows, for example, snippets of a data specification for a virtual drone NAVAIR X47-B Drone (the data is publicly available on the Internet) that includes attributes covering crew, length, payload, wingspan, height, maximum allowable payload, and performance specifications for achievable performance (e.g., cruise speed and maximum speed).

```
[java]
[java] LIST OF COMPONENTS
[java] ==========================================
[java]
[java] Component: ID = Drone-X47-B, type = UAV
[java] -------------------------------------------------------
[java] Description = [ NAVAIR X47-B Drone ]
[java] -------------------------------------------------------
[java] No nodes          = [ 0.0 ]
[java] No ways           = [ 0.0 ]
[java] No attributes     = [ 6.0 ]
[java] No parameters     = [ 7.0 ]
[java] No specifications = [ 5.0 ]
[java] No ports          = [ 0.0 ]
[java] -------------------------------------------------------
[java] Attribute  1:  [ key, value, units ] = [ "length", "5.5", "m" ]
[java] Attribute  2:  [ key, value, units ] = [ "wingspan", "10.0", "m" ]
[java] Attribute  3:  [ key, value, units ] = [ "maxRange", "3,889", "km" ]
[java] Attribute  4:  [ key, value, units ] = [ "maxSpeed", "1,073", "km/hr" ]
[java] Attribute  5:  [ key, value, units ] = [ "maxEndurance", "6.0", "hr" ]
[java] Attribute  6:  [ key, value, units ] = [ "maxAltitude", "43,000", "ft" ]
[java] -------------------------------------------------------
[java] Parameter  1:  [ name, value, units ] = [ speed         , "200.0", "m/sec", "Real" ]
[java] Parameter  2:  [ name, value, units ] = [ weight        , "0.0", "kg", "Real" ]
[java] Parameter  3:  [ name, value, units ] = [ altitude      , "2500.0", "m", "Real" ]
[java] Parameter  4:  [ name, value, units ] = [ range         , "4,500.0", "km", "Real" ]
[java] Parameter  5:  [ name, value, units ] = [ endurance     , "0.0", "hr", "Real" ]
[java] Parameter  6:  [ name, value ] = [ latitude      , "0.0", "null" ]
[java] Parameter  7:  [ name, value ] = [ longitude     , "0.0", "null" ]
[java] -------------------------------------------------------
[java] Behavior: ID = #B001
[java] -------------------------------------------------------
[java]
[java] Specification  1: ID = S01, type = Performance ...
[java] -------------------------------------------------------
[java] Description = [ Maximum takeoff weight ]
[java] -------------------------------------------------------
[java] Attribute  1:  [ key, value] = [ "expression", "weight < maxWeight" ]
[java] -------------------------------------------------------
[java] Parameter  1:  [ name, value, units ] = [ "maxWeight", "20,215", "kg" ]
[java] Parameter  2:  [ name, value, units ] = [ "#weight", "0.0", "kg" ]
[java] -------------------------------------------------------
[java] Evaluation: weight < maxWeight --> true ...
[java] -------------------------------------------------------
[java]
[java] Specification  2: ID = S02, type = Performance ...
[java] -------------------------------------------------------
[java] Description = [ Maximum re-fueled range ]
[java] -------------------------------------------------------
[java] Attribute  1:  [ key, value] = [ "expression", "range < maxRange" ]
[java] -------------------------------------------------------
[java] Parameter  1:  [ name, value, units ] = [ "#maxRange", "3,889", "km" ]
[java] Parameter  2:  [ name, value, units ] = [ "#range", "4,500.0", "km" ]
[java] -------------------------------------------------------
[java] Evaluation: range < maxRange --> false ...
[java]
[java] -------------------------------------------------------
[java] Specification  3: ID = S03, type = Performance ...
[java] -------------------------------------------------------
[java] Description = [ Maximum speed ]
[java] -------------------------------------------------------
[java] Attribute  1:  [ key, value] = [ "expression", "speed < maxSpeed" ]
```

Figure 4. Preliminary implementation of component specifications and measures of effectiveness within the system data model.

Figure 4 show snippets of program output after the data model has been imported into System Data Model and the constraints and specifications have been evaluated. The evaluation of mathematical constraints and specifications is currently handled by Java software associated with the System Data Model, but in future versions, will most likely be implemented as back-end functions associated with domain ontologies and rules (see Figure 1 and the left-hand side of Figure 2).

Future Work. Semantic counterparts (ontologies and rules) to the system data model tags (e.g., <component>, <specification>, <constraint> and <requirement>, etc) and requirements (e.g., <requirement>) are a work in progress. We have in mind that future version of our work will allow for the assembly of graphs of textual requirements and mathematical constraints, with a systems engineer using the latter to formally verify the content of textual requirements. We are exploring opportunities for using ``requirements templates'' and natural language processing to improve the way in which textual requirements are transformed into mathematical constraints. This process is complicated by a host of very practical problems such as the presence of physical units, acronyms, hierarchies of acronyms, and presence of references to spatial and temporal content. Our supposition is that if these factors can be accurately identified, then the quality (accuracy) and usefulness of semantic representations (ontologies and rules) will also increase.

PROJECT 2: System-Level Data Model and Ontologies for Statechart Behaviors.

Research Team: Mark Austin

Project Summary. As illustrated along the right-hand side of Figure 1, the pathway from Skyzer mission operations to scenarios, path planning, scenario refinement, generation of events and response of the semantic graph models requires that we explicitly represent and execute component- and system-level behaviors. A reasonable starting point is to assume that all components – physical and otherwise – have behaviors that can be adequately represented by sequences of finite states (or statecharts). System level behaviors will correspond to a loosely coupled network of communicating statechart machine models. At both the component and system levels, behaviors will correspond to sequences of transitions between states, subject to guard conditions that trace directly back to mathematical constraints and textual requirements.

Figure 5 shows, for example, a simplified model for UAV behavior (including the various states and transitions) and modes of flight operation (i.e., manual flight versus autonomous flight).

From an end-user perspective, an obvious benefit of this capability is that executable statecharts provide visual feedback on what components in the system are doing. From a developer standpoint, statechart models provide a means for the systematic development and verification of rules. For instance, the state "mission operations'' will have a collection of rules that apply when the drone is within a mission area. The latter is a spatio-temporal context.

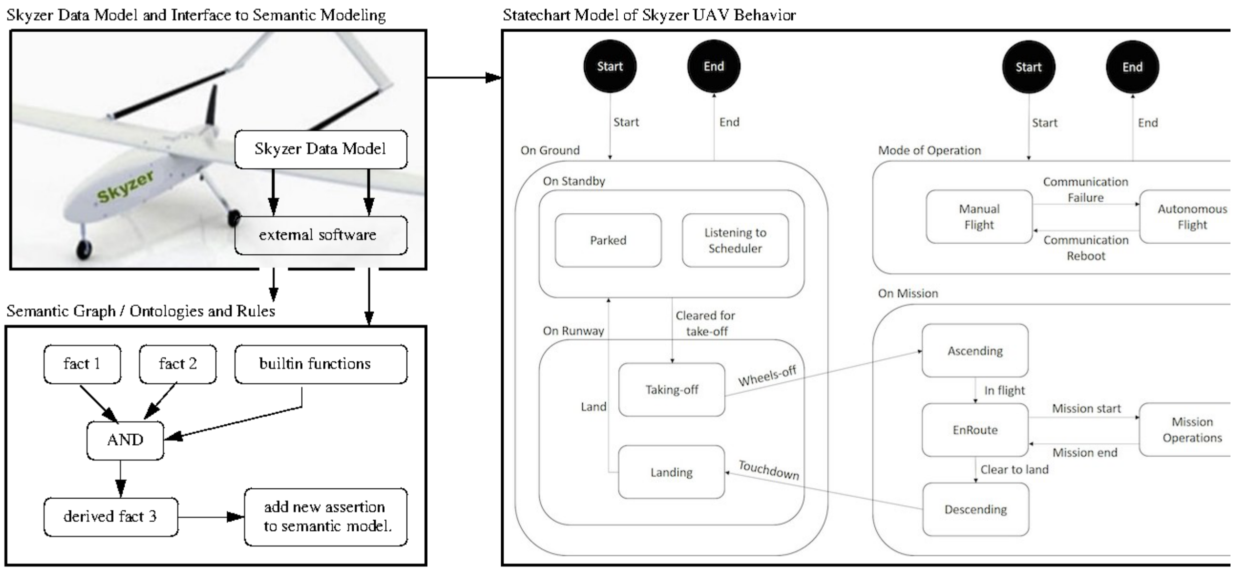


Figure 5. Simplified finite state machine model for UAV flight operations.

Results. We have implemented a statechart data model that includes support for the modeling of composite hierarchies of states and transitions, execution of guard conditions, as well as support for execution of concurrent statechart models. The visualization of models is implemented in JavaFX. Models and views are tied together using the model-view-controller software design patterns. The statechart model accepts and responds to streams of events as input. Figures 6 and 7 show, for example, snapshots of concurrent statechart behavior for a drone that traverses a prescribed flight path but at some point suffers a communications failure – the mode of flight operations switches from manual to autonomous flight.

At this point the states, transitions, and graphical layout are manually specified. While this process is very tedious (a regular engineer would just say too complicated, forget it), we believe that the assembly of executable behavior can be automated by having the statechart data model visit the system data model and gather all of the relevant data on states, transitions, guards, and visual layout defined between <behavior> … </behavior> tags. The key advantage of this is that you'd only need to create the model once! From complexity standpoint, we believe the implementation would be no more difficult than writing a parser or small compiler.

Future Work. Simplified scenarios of drone behavior that include movement of a drone along a prescribed pathway to/from a mission operations area, and injection of faults into the communication system, will be simulated in Whistle.

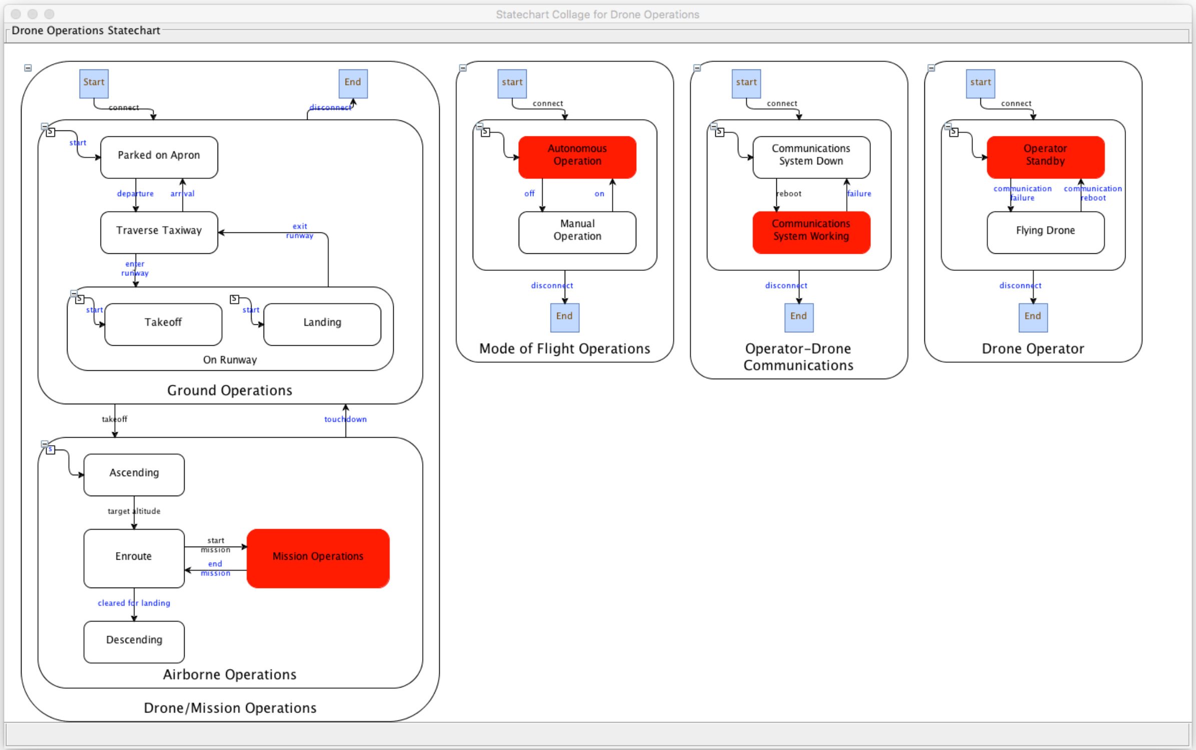


Figure 6. Drone is conducting mission operations. Mode of flight operations is autonomous, operator-drone communications are working, and drone operator is on standby.

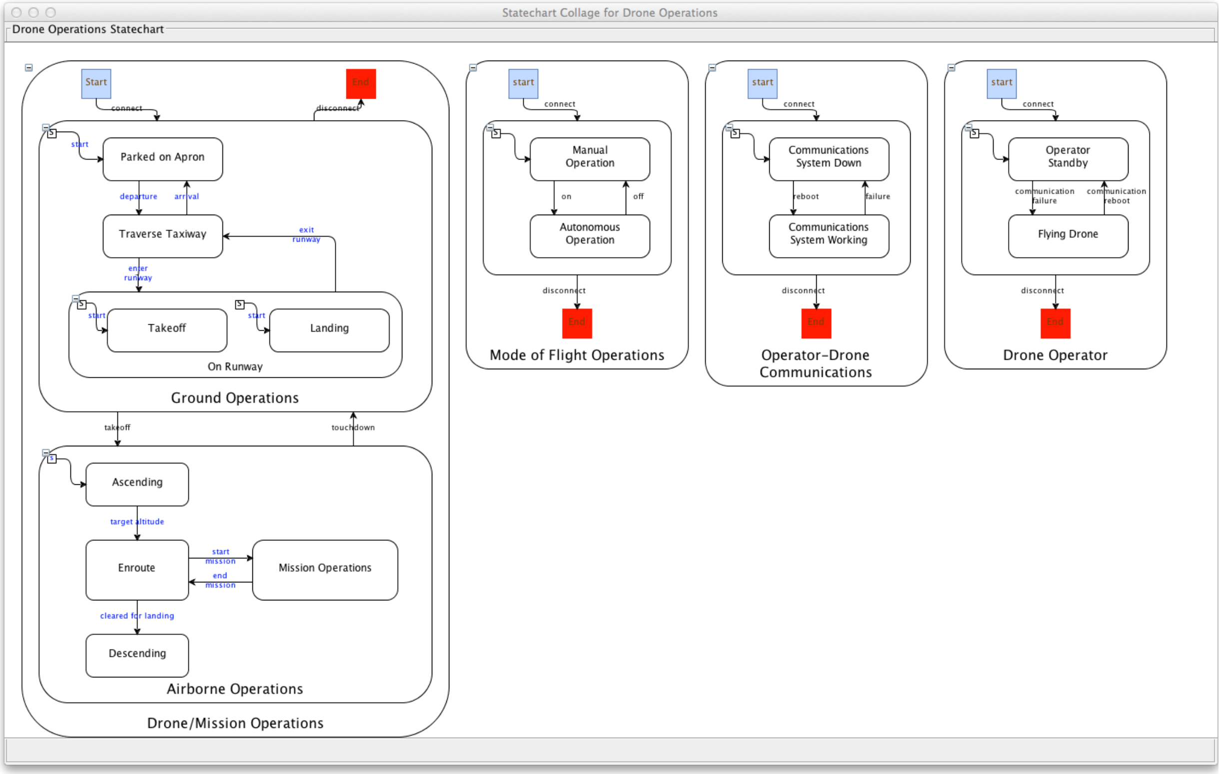


Figure 7. Distribution of states at completion of the mission operations.

Publications:

1. Coelho M., Austin M.A., and Blackburn M.R., The Data-Ontology-Rule Footing: A Building Block for Knowledge-Based Development and Event-Driven Execution of Multi-Domain Systems, Systems Engineering in Context - Proceedings of the 16th Annual Conference on Systems (CSER 2018), Springer, Charlottsville, VA, May 8-9 2018.

2. Austin M.A., Coelho M.C., and Blackburn M.R., Semantic Modeling and Event-Driven Execution of Multi-Domain Systems and System of Systems with the Data-Ontology-Rule Footing, System Engineering, Submitted June 2018. (Revisions in progress).

C. INTEGRATING SYSML, MBSEPAK AND MODELCENTER

Author: John Dzielski, Mark Blackburn

Implementing a Decision Framework in SysML Integrating MDAO Tools (Published in INCOSE Insight)

Abstract

This article describes an implementation of a decision framework modeled in SysML that can be executed with two different parametric analyzers. One of those analyzers provides the kind of cross-tool and cross-domain integration of simulation and analysis tools that will ultimately be required to implement model based design at large scales. The paper describes the decision framework and illustrates its implementation in SysML in the context of the design of a notional surveillance drone. The paper concludes with some observations about future directions and some of the difficulties that were encountered.

Keywords: SysML, decision framework, MDAO.

C.1 Introduction

Figure 1 illustrates a simplified perspective on a traditional systems engineering process (Blackburn 2018). The process is abstracted from a more detailed process described in (Cilli 2015). The process begins with a concept of operation (CONOP) phase that defines a need or gap to be filled by a system. The need is defined based on a business or mission analysis, or based on a set of stakeholder needs. The "What" part of the process involves defining the system-level requirements along with the objective measures and key performance parameters (KPPs) that will be used to evaluate a candidate solution. During the "How" part of the process, different system architectures are synthesized and sets of alternatives for each architecture are parameterized. During the "How well" phase, modeling, simulation, and analysis are used to analyze how effectively each alternative performs relative to the objective measures and KPPs. The role of a decision framework is to collect the objective measures and KPPs and present it to stakeholders in a way that allows them to determine which alternatives best suit their needs. In any real process, there will be multiple stakeholders who place different value or weight on each of the measures and KPPs, and it is important to be able to present to the decision makers the trade-offs that exist between them. This article describes a framework for doing this and a SysML implementation that uses a multi-dimensional design and optimization (MDAO) tool to implement it in the context of a notional surveillance drone problem.

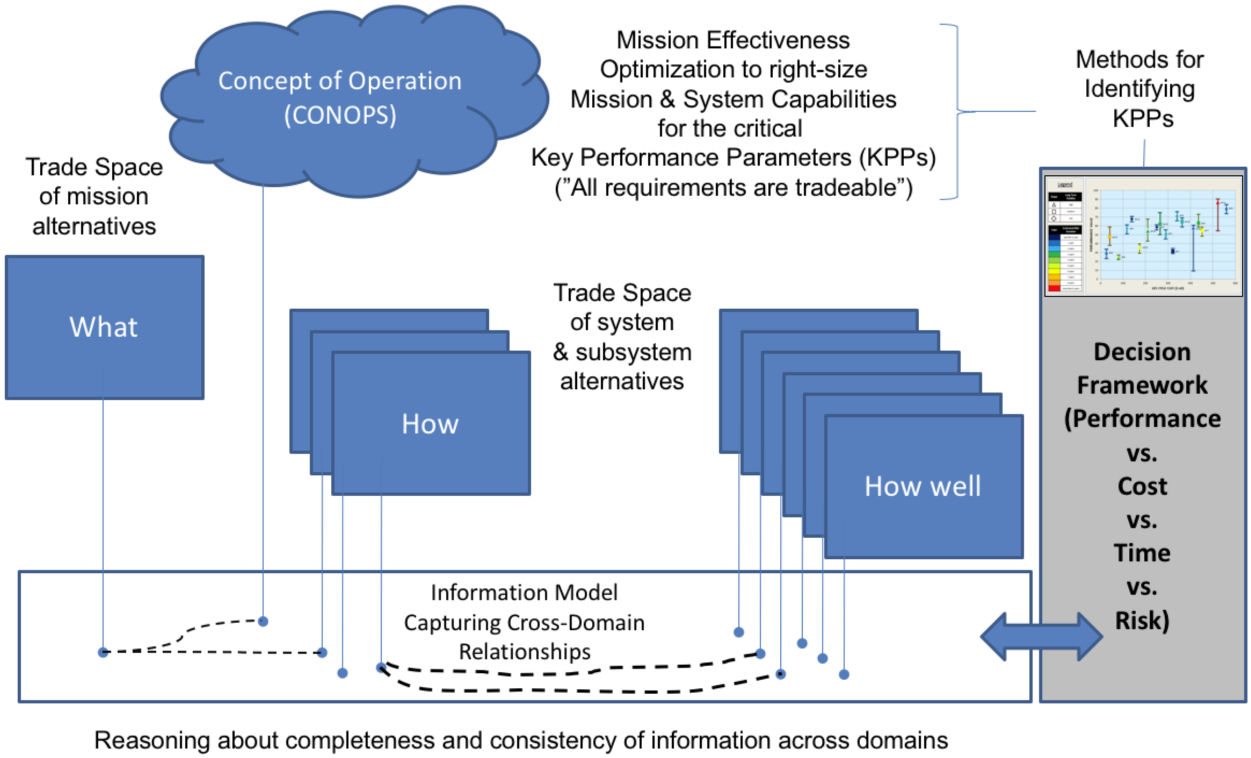


Figure 1. Simplified perspective of a systems engineering process (Blackburn 2018).

A successful transition from a document-based systems engineering process to a model-based process will require an ability to perform cross-domain and cross-tool analysis when evaluating the characteristics of a system. In the context of Figure 1, this is the process of determining the "How well" based on the "How." In a traditional process, the teams and tools used to perform these analyses are typically not linked digitally. Furthermore, the effort required to link these tools may be prohibitive and the linkages may ultimately be brittle if the integrator does not have control of the tools or their APIs. Finding efficient ways to link these analyses and capture the linkage in a digital model will be critical to enabling digital systems engineering processes.

ModelCenter® is a multi-disciplinary design and optimization (MDAO) platform that provides automation of cross-tool workflows in support of engineering analysis. The tool allows users to implement workflows that link analyses performed in a variety of widely used tools such as Matlab®, NASTRAN®, Ansys®, and SolidWorks®. This is only a partial list of tools that have been integrated, and the tool also allows integration of user-owned tools and workflows. ModelCenter® also provides integration with SysML through integration with MagicDraw® either through ModelCenter® or through a plugin to MagicDraw® called MBSEPak®. The implemented capabilities provide a means to automatically create complex workflows in ModelCenter® that are defined in the parametric diagrams of a SysML model, and to execute the workflow to perform cross-domain analyses and to execute trade studies.

The role of a decision framework is to relate the characteristics of a set of design alternatives selected by engineers to the value placed on those alternative by the stakeholders who are the owners or users and the decision makers. The output of the cross-domain analysis is a set of values for metrics and KPPs that are not directly comparable to one another. One reason that they are not directly comparable is simply because of differences in units. Another is that the numerical values may differ vastly in magnitude (e.g. milligrams vs. kilograms). The Integrated Systems Engineering Decision Management (ISEDM) Framework proposed in (Cilli 2015) provides a way to normalize these quantities in a way that expresses their value to a given stakeholder. Furthermore, different normalizations can be applied to reflect the needs of different stakeholders. Finally, data visualization tools can be used to understand the tradeoffs that exist within a set of alternatives and to guide the creation of new alternatives.

This article describes the results of an effort to implement a reference decision framework in SysML that performs the requisite analysis associated with a set of alternatives using an MDAO tool. The reference decision framework is described in the next section. In the following section, an implementation of the decision framework in SysML is described. To provide context, a simple example of a problem of designing a surveillance drone is introduced. To help understand the affect the choice of MDAO tool has on the process of building the SysML model, the framework was implemented to work simultaneously with a second tool Cameo Simulation Toolkit® (CST) from MagicDraw®. CST is marketed as a parametric solver for SysML diagrams. The final section discusses some conclusions drawn from using the tools and also discusses potential broader impacts associated with the framework.

C.2 Decision Framework

The Systems Engineering Body of Knowledge (SEBoK, 2017) identifies the development of objectives and measures as a critical part of a decision process. The objectives are the high-level concepts that give value to stakeholders such as performance, cost, and risk. For each objective, one or more measures are defined that quantitatively characterize the objective. Objectives and measures may be defined in hierarchies, and are often defined by a functional decomposition.

A second part of the process identified in (SEBoK, 2017) and discussed in the context of Figure 1 is the creation of alternatives. This process involves creating product architectures whose components provide the functionality to realize the objectives. A critical part of this process is identifying the key properties of an alternative and the characteristics that derive from those properties (Weber 2014)[25]. Here, properties are the attributes of a design that can be directly selected or influenced by the designer. Characteristics are those attributes that are indirectly influenced. For example, a designer can select a part's shape and what it is made of, but the part's weight results from those decisions.

In his thesis, (Cilli 2015) introduced the assessment flow diagram (AFD) as a tool for tracing the relationships between the properties of a system and the metrics and KPPs defined to measure its performance which will be referred to here as measures. Figure 2 shows an example AFD. The properties are identified with the "physical means" corresponding to the system architecture and the properties of its subsystems. At the top of the diagram are the list of measures and KPPs. In the figure, the "intermediate measures" are referred to as characteristics here. The AFD effectively describes a workflow for computing the measures and shows traceability between properties and measures.

[25] The use of the terms property and characteristics used here is reversed from that in the reference.

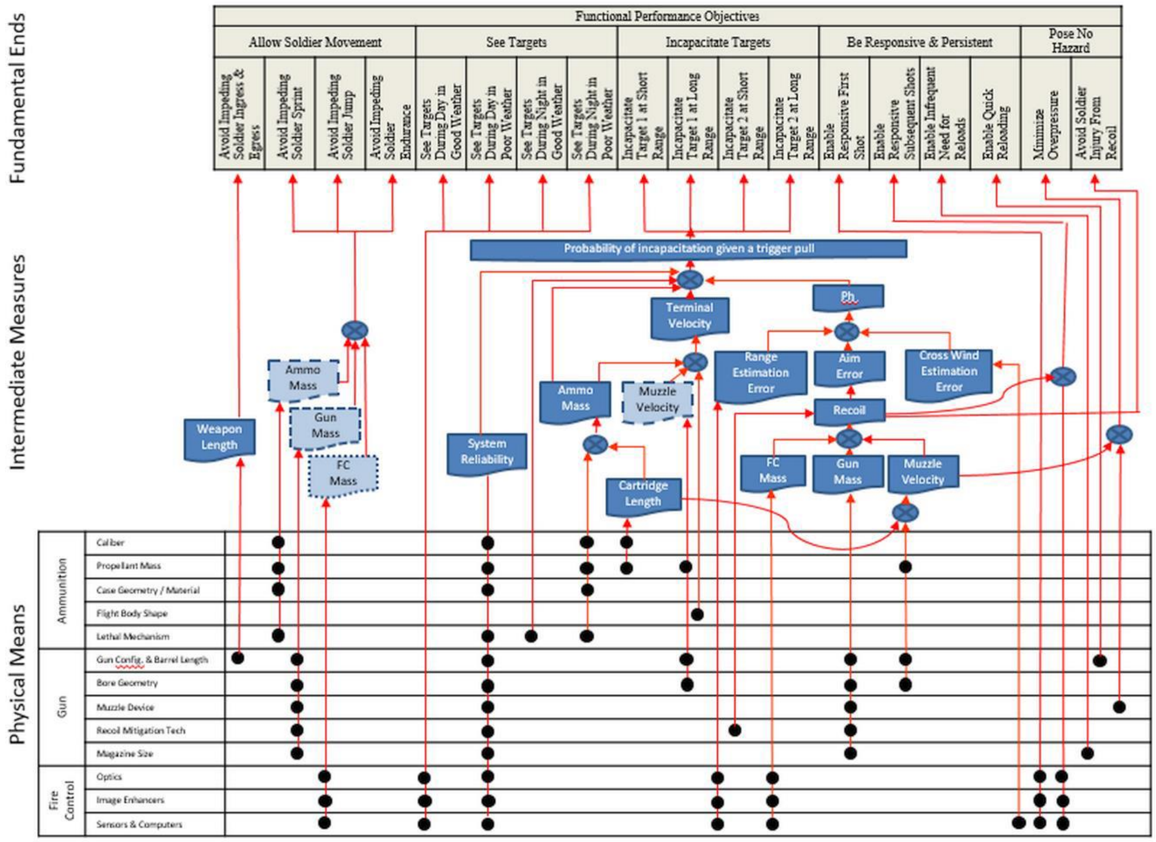


Figure 2. An example assessment flow diagram (Cilli, 2015).

(Cilli 2015) introduces the measure[26] scorecard as a tabular way of capturing and tracking the measures associated with alternatives in an analysis of alternatives or a trade study. The scorecard can be arranged in a spreadsheet with each row corresponding to an alternative and each column corresponding to one of the measures. Similarly, (Cilli 2015) introduces the value scorecard as a way of capturing and tracking the value applied by one or more stakeholders to the set of metrics associated with an alternative. For each entry in the measure scorecard there is a corresponding entry in the value scorecard. Each value is a monotonic function of the corresponding measure and maps the numerical value of the measure to a value scale of 1-100. An illustrative example of shapes can be found at (SEBoK, 2017), and one suggestion is that a value of 0 be associated with a measure that has not utility to a stakeholder and a value of 100 with a measure such that larger values provide no additional utility.

C.3 SysML Implementation of the Decision Framework

Figure 3 illustrates the ISEDM Framework described in the previous section. This section describes an implementation of that framework in SysML in the context of notional Unmanned Aerial System (UAS) surveillance drone. On the bottom left side of the diagram are steps associated with creating the metrics and KPPs. On the lower right are steps associated with creating the alternatives. These steps are creating the generic and specific structures or

[26] The thesis uses the term "consequence" instead of the word measure used here. The latter is used here because it is believed to be more descriptive.

architectures of the alternatives, and generating the alternatives themselves. This process identifies the properties that define the individual alternatives. The next step in the process is to model what in the AFD is called the intermediate measures and measures, and what are called characteristics here. This has been done with SysML parametric diagrams and constraints and produces results equivalent to the measure scorecard. Finally, an implementation for computing the values of alternatives is introduced.

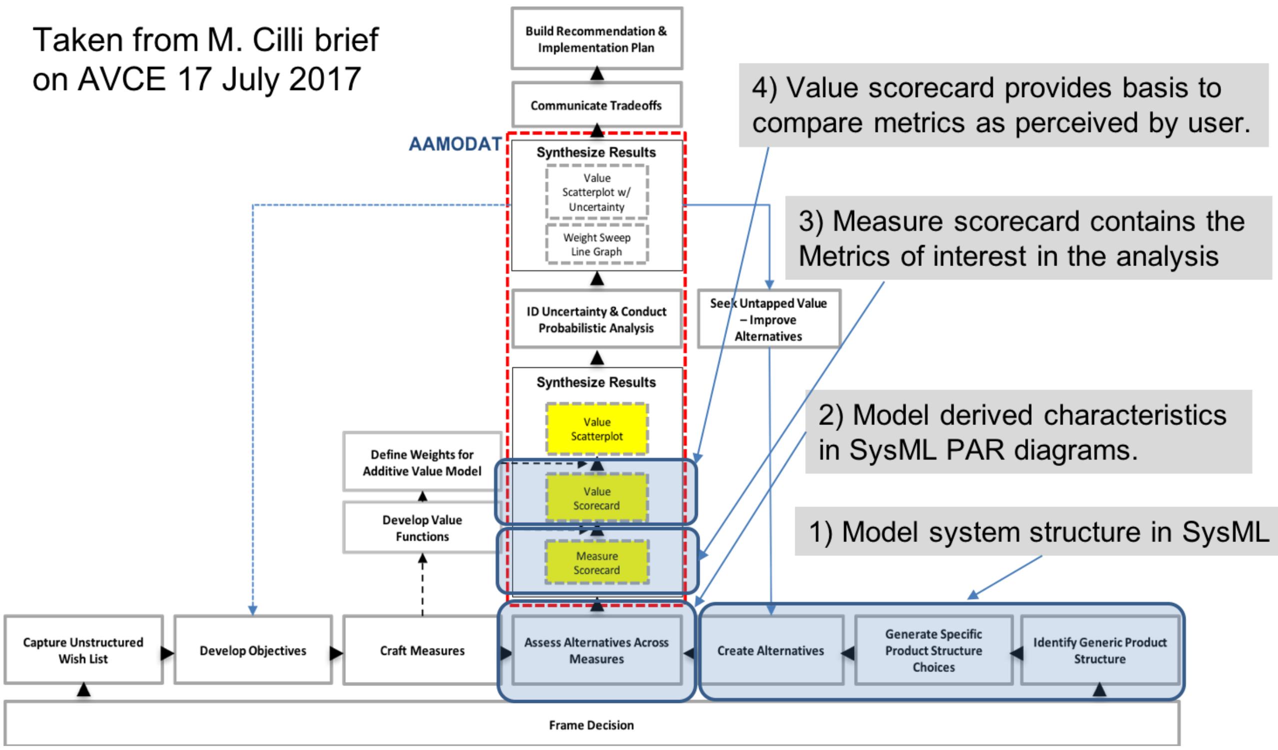


Figure 3. Annotated graphic illustrating a decision framework and steps implemented in SysML (used by permission)

The thesis (Cilli 2015) employed an example of an UAS for surveillance to illustrate the concepts, and that example has been adapted to demonstrate the application of the decision process here. The structure of a UAS is shown in Figure 4. The UAS consists of an Air Vehicle and a Payload. The Air Vehicle decomposes into an Air Frame with properties wingspan and altitude and an Engine with an engine that is either “Electric” or “Piston.”[27] The Payload decomposes into a pair of Imaging Sensors and a CommLink. The CommLink’s property is its weight and the Imaging Sensors properties are field-of-view, number of pixels, and pixel size. This set of values defines the properties that will make up each instance of an alternative.

[27] It would be natural to use an enumerated type here, but not all parametric analyzers that were used in this study worked with enumerated types.

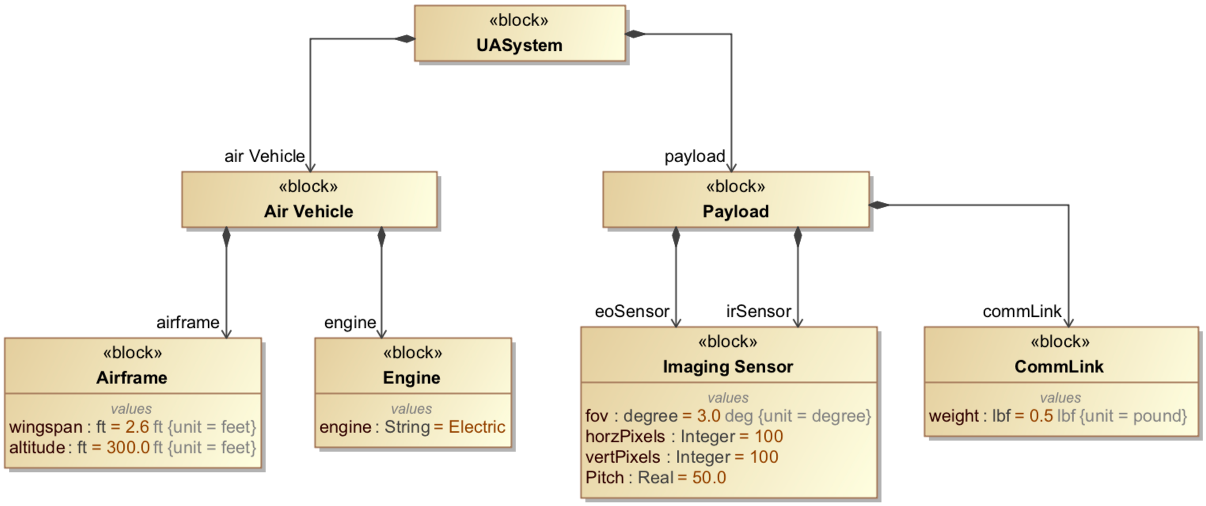


Figure 4. Structure of a UASystem showing the system properties.

The parts of a UAS along with their characteristics are shown in Figure 5. These are the intermediate measures in the AFD that are not necessarily directly of interest to the stakeholders as metrics or KPPs, but necessary to the calculation of those quantities. The names of the characteristics are largely self-explanatory and are indicated in the diagram as derived quantities. These quantities are calculated by defining constraint blocks in SysML and then binding the ports on the constraint blocks to parameters and other characteristics in parametric diagrams. The workflows required to compute the characteristics are created automatically in ModelCenter running as a stand-alone program or its MagicDraw plugin MBSEPak. Cameo Simulation Toolkit® provides a simulation capability to evaluate parametric diagrams. The measures associated with an alternative are the parameters that matter to the stakeholders or users of the system. A list of measures with descriptive names for the UAS are also shown in Figure 5.

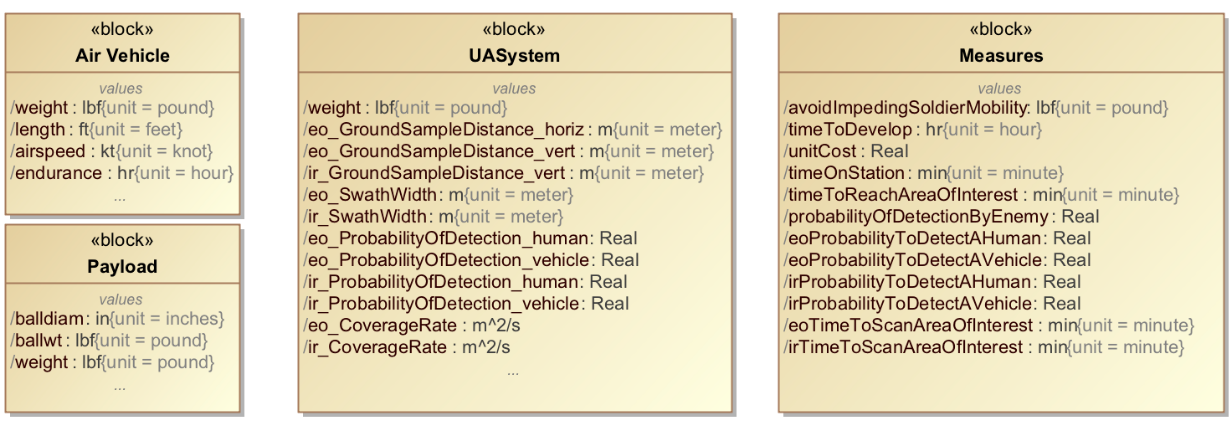


Figure 5. Blocks showing the characteristics and measures of the system derived from properties.

The constraint used to calculate values from measures is shown in Figure 6 along with two examples of generalized value blocks. A stakeholder selects a numerical value for each measure that is a walk-away value that is too small or large to be useful, a marginally acceptable value, a goal or target value, a value that would be highly desirable, and a value where larger or smaller values provide no additional usefulness. Default values for these points are 1, 10, 50, 90, 100, where a low value of 1 was selected to that ratios of values are always numerically valid. The two examples show a value function that decreases as the measure increases (weight) and increases with the measure (time on station).

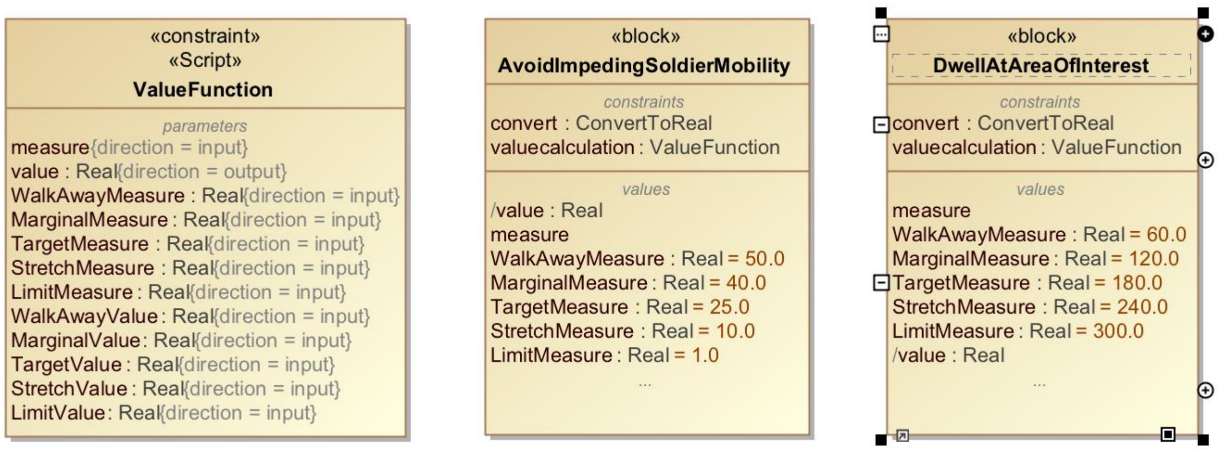


Figure 6. Constraint block defining the value function and two examples of value blocks associated with the UAS.

C.4 Defining a Trade-Study

A trade study can be built in SysML on top of the structures previously defined. An example trade study is shown in Figure 7. The study begins with the definition of a set of alternatives for the Payload and the Air Vehicle. These alternatives can be manually created as instances in the model, or read in from a formatted file or spreadsheet. An activity combines the instances of these alternatives in all possible pairings and creates an ordered list of UAS alternatives. A set of measures can be computed based on the alternatives and a set of values associated with those measure computed. How the measures and values are computed depends on the capabilities of the parametric analyzer or MDAO tool being used. The models built here used activities to apply the analyses. In the example below a trade study was implemented in Cameo Simulation Toolkit®, an activity sorted through the values for each alternative and eliminated the solutions that were not Pareto optimal. ModelCenter® has a number of built-in capabilities that support MDAO. Analysis of alternatives can be pursued there using built-in design of experiments capabilities or using functionality supporting numerical optimization. In either tool, alternatives can be automatically created as instances and saved in the model containtment tree.

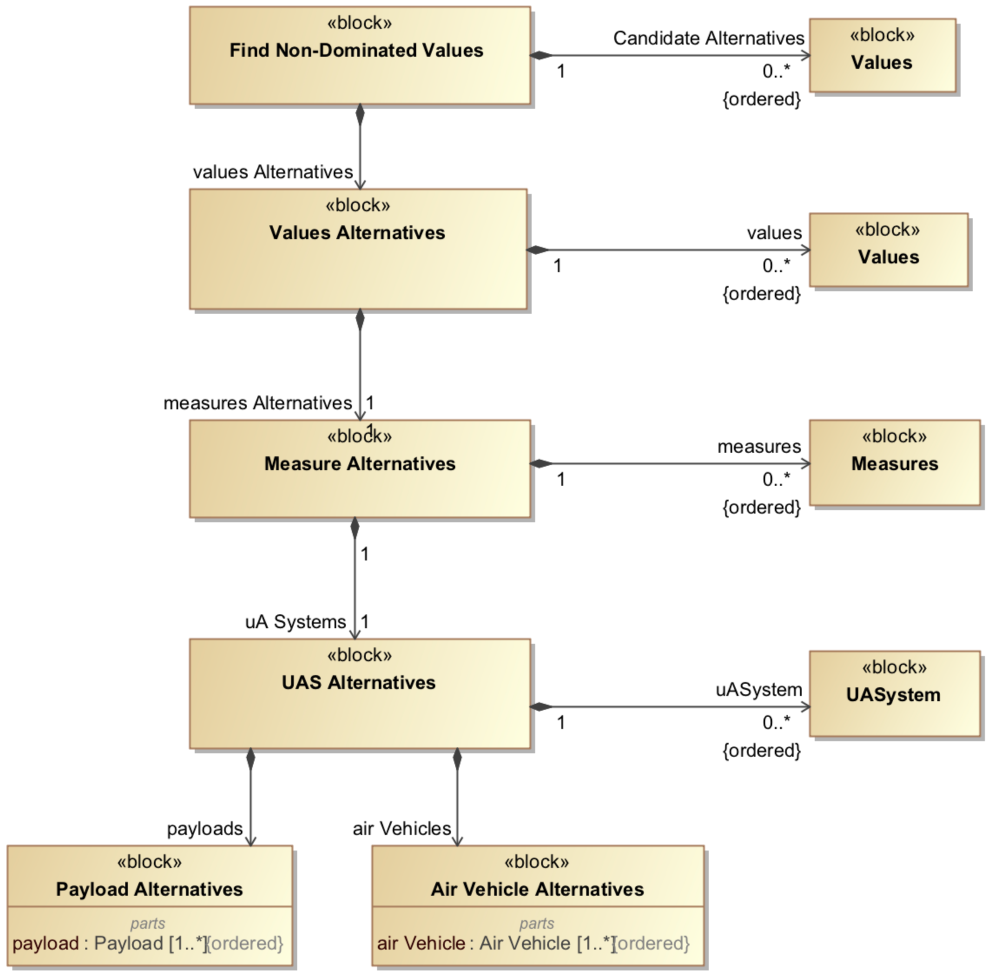


Figure 7. An example trade study built in SysML.

C.5 Summary and Conclusions

One of the goals underlying this effort was to show that it was possible to formalize a decision framework in SysML that could be implemented in a way that incorporated an underlying framework for cross-domain analysis. The ability to implement complex analyses currently done by independent teams and decoupled tools is critical to enabling a transition to model-based engineering. ModelCenter® is one tool that provides integration between tools used on large-scale engineering problems indicating the feasibility of linking model and analysis capabilities. Ultimately, a successful transition to model-based engineering will require capabilities that provide model integration that are tool agnostic. Sematic web technologies (ontologies) are being investigated as a possible means for addressing this need (Bone et al., 2018). The vision is that if analysis tools can have their interfaces described in a standard way, then tool integration can be handled automatically.

Another challenge that was identified as part of this effort has to do with what is standardized by the SysML standard. SysML defines a constraint as a relationship that must hold between a set of values bound to ports. The standard does not distinguish between values that an engineer might consider to be the inputs and outputs to a calculation. A consequence of this is that a set of parametric diagrams does not define a unique or unambiguous workflow for evaluating them. Also, tools may not create workflows for all valid SysML diagrams, and SysML diagrams that can be evaluated in one tool may not evaluate correctly in another.

C.6 Disclaimer

Certain commercial software products are identified in this material. These products were used only for demonstration purposes. This use does not imply approval or endorsement by Stevens or SERC, nor does it imply these products are necessarily the best available for the purpose. Other product names, company names, images, or names of platforms referenced herein may be trademarks or registered trademarks of their respective companies, and they are used for identification purposes only.

C.7 References

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C.8 Rules to Follow for Using MBSEPak® and Cameo Simulation Toolkit®.

This is an extra section included in this report that was not included in the INCOSE Insight submission.

When building models with parametric diagrams that must be executed with MBSEPak® or Cameo Simulation Toolkit (CST), there are certain rules that must be followed to ensure that the models execute with both tools. This section explains the rules that were identified during this project. These comments are valid for MagicDraw® version 18.5 SP3. Some issues are known to have been fixed in LTR 19.

Blocks should be related by directed composition relationships only. CST does not recognize blocks related by reference (aggregation or association). MBSEPak® will return an error about algebraic loops if relationships are undirected.

When building a model, diagrams should be tree structured. This means that from a parent block, there should be a single path following composition relationship to each child if that child is intended to represent a single model element. Both CST and MBSEPak will create an independent block and analysis flow for each path to a block.

Enumerated types are not fully supported in MBSEPak®. Problem appears when using instances. Use a string type instead.

Initialization of numerical arrays is not supported in MagicDraw®. This is fixed in LTR 19.0.

When creating instances in MagicDraw®, occasionally it will leave a slot value untyped or defined to be an opaque type. The model will simulate with CST but not in MBSEPak®.

When creating instances, parametric diagrams are not automatically executed. In fact, slot values may not be present at all. The MBSEPak® workflow requires that the user "Run" the model. This step will execute parametrics and assign values to slots. Using CST to simulate a block or instance will produce results in the simulation window but the results will not save back to the containment tree. The way to do this is to create a simulation configuration block that has the instance as its executionTarget and resultLocation.